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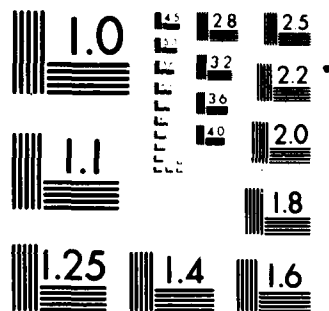
AIR FORCE TECHNICAL APPLICATIONS CENTER ALEXANDRIA VA--ETC F/G 17/10
A CONCEPT REVIEW OF AN UNDERGROUND HIGH EXPLOSIVE TEST PROGRAM --ETC(U)
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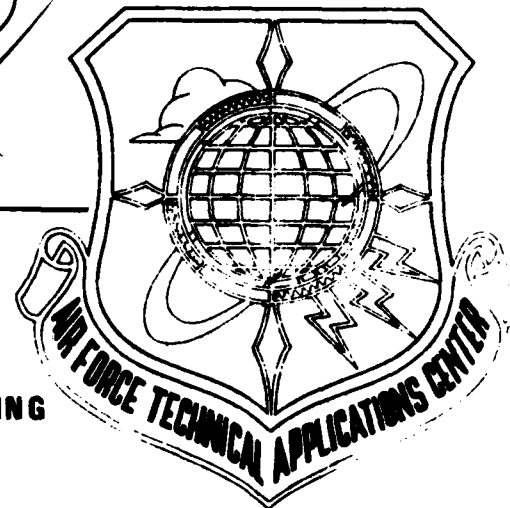
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**A CONCEPT REVIEW OF AN UNDERGROUND
HIGH EXPLOSIVE TEST PROGRAM SUPPORTING
COMPREHENSIVE TEST BAN MONITORING
RESEARCH**

Gilbert W. Ullrich

31 December, 1979

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**VELA Seismological Center
Air Force Technical Applications Center
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER VSC-TR-79-01	2. GOVT ACCESSION NO. AD-A093410	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Concept Review of an Underground High Explosive Test Program Supporting Comprehensive Test Ban Monitoring Research		5. TYPE OF REPORT & PERIOD COVERED Tech. Rep. 1 Jun 79 - 31 Dec 79
7. AUTHOR(s) Gilbert W. Ullrich		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS VELA Seismological Center 312 Montgomery Street Alexandria, VA 22314		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Technical Applications Center/TD Patrick Air Force Base FL 32925		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS In-House
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE 31 December 1979
		13. NUMBER OF PAGES 327
		15. SECURITY CLASS. (of this report) Unclassified
16. DISTRIBUTION STATEMENT (of this Report) Approved for Public Release, Distribution Unlimited		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) High Explosive Tests Underground Nuclear Explosions Seismic Research Seismology VELA Evasion Cavity Decoupling		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The detection and identification of underground nuclear tests, during a Comprehensive Test Ban (CTB), places new, and stringent, requirements on monitoring systems. In particular, because of the factor of about 70 reduction in apparent yield that can be achieved by cavity decoupling, seismic monitoring must extend to short period magnitudes in the range of 2.5 to 3.5. The apparent absence of mechanical effects data from suitable underground explosions in this magnitude range makes planning for CTB monitoring difficult. In this paper, we find that tamped high explosive charges, in the 40 to 320 ton yield range, may serve		

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Underground High Explosive Test
Program Supporting Comprehensive
Test Ban Monitoring Research

by Gilbert W. Ullrich

Abstract

The detection and identification of underground nuclear tests, during a Comprehensive Test Ban (CTB), places new, and stringent, requirements on monitoring systems. In particular, because of the factor of about 70 reduction in apparent yield that can be achieved by cavity decoupling, seismic monitoring must extend to short period magnitudes in the range of 2.5 to 3.5. The apparent absence of mechanical effects data from suitable underground explosions in this magnitude range makes planning for CTB monitoring difficult. In this paper, we find that tamped high explosive charges, in the 40 to 320 ton yield range, may serve as surrogate sources for obtaining this mechanical data. Therefore, we recommend a high explosive test program to obtain mechanical data that would support research aimed at providing the capability to monitor a Comprehensive Nuclear Test Ban Treaty.

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I INTRODUCTION

Since the beginning of Nuclear Test Ban Treaty negotiations, the national policy of several nations, including the United States, has been to establish a Comprehensive Test Ban (CTB) Treaty to prohibit nuclear weapons tests. Indeed, considerable progress over the past 20 years has been made toward that objective in that all but underground nuclear testing has been prohibited by several countries, and even underground nuclear testing has been limited. However, the CTBT has still not been achieved because of the difficulties in verifying the abandonment of underground nuclear tests.

This verification requires the ability to detect and identify suspicious underground events and then to show that those events were indeed nuclear explosions. This detection and identification of underground nuclear tests has historically been accomplished by seismological techniques. However, the establishment of a CTB would place new, and stringent, requirements on monitoring such a treaty. In particular, the well recognized and publicly documented (Latter et al., 1961; Springer et al., 1968; Rodean, 1971, 1979; Dahlman and Israelson, 1977; and many others) CTB evasion technique of "Cavity Decoupling" results in two major difficulties for CTB monitoring by seismic methods. First, because of the factor of about 70 reduction in apparent yield thought to result when this technique is employed, nuclear explosions of several kilotons may be difficult to detect even with national seismic stations. Second, again because of the large reduction in apparent yield, even if the seismic signal from a decoupled test is detected, it must also be identified; not only from all earthquakes, but also from buried, multi-ton, high explosive detonations that may be used for geophysical purposes (Warren et al., 1966; Lewis and Meyer, 1968 for examples).

In this paper we discuss the concept of a research program of dedicated high-explosive experiments that would provide basic mechanical

effects data that are critical to preparations for monitoring a CTBT when evasion by decoupling is considered. The principal objectives of the program would be to evaluate, at large scale, (a) yield scaling for deeply buried charges in salt, (b) the equivalence between decoupled nuclear explosions (NE) and tamped high explosive (HE) charges, (c) the equivalence between tamped NE and tamped HE charges, and (d) the usefulness of HE tests as a full-scale research tool for nuclear monitoring research. Major additional, or alternative, objectives could include basic research in source region effects, regional seismology, and provision of test environments for evaluation of various CTBT monitoring concepts. These objectives, when combined, will support directly the principle issues of low yield CTBT evasion and contribute significantly to basic research in seismic effects from underground explosions in salt.

The program concepts discussed here are divided into a basic program, and potential enhancements in experimentation, measurements, and analysis. The cost estimates are made to provide a cost/benefit measure only and are based on the best available information at this time with no allowance for inflation. These estimates, then, are not to be construed as budgeting figures. The conceptual program is estimated to require approximately two years to accomplish after completion of detailed planning and budgeting activities and an implementation decision. Of these two years, one year would involve procurement and fielding activities, three to six months for test accomplishment, and the remainder for analysis and reporting. During the planning activities, information related to test site selection, environmental impact, explosive charge material, explosive charge emplacement procedures, and detailed experimentation will need to be generated. After discussing the program concept, we shall briefly consider alternatives to that program.

We conclude from this concept discussion that tamped high explosive tests in the 40 to 320 ton yield range may be useful experiments that are

feasible and cost effective. We believe that such experiments could provide extensive mechanical effects data that would fill in an amplitude range which becomes critical when low yield evasion of a CTB Treaty is considered; and, at the same time, provide a useful focus for basic seismological research. We recommend, therefore, that long lead studies in test site selection, environmental impact, and specific engineering definition be combined with detailed program planning so that a decision on program implementation can be made as soon as possible.

II UNDERGROUND HIGH EXPLOSIVE TEST PROGRAM CONCEPTS

a. Logical Background. Rodean first described a simple model for the "Conditions for Detection of 6 KM/S Crustal P Waves from Explosions in Cavities" at the DARPA Conference on Decoupling in February, 1979, that he later expanded in the report, Optimum Frequencies for Regional Detection of Cavity - Decoupled Explosions (Rodean, 1979). Murphy (Appendix A) divided Rodean's simple model into source, propagation path, and sensor-site noise components in his memo "A Bounding Analysis of Factors Influencing the Detection of Decoupled Explosions at Regional Distances." Ullrich (Appendix B), in addition to adding discrimination considerations to the detection discussion, suggested that even if data transmission and use were assumed to be perfect, a model of the deployed sensor system should be added to complete the logical "Framework." Thus, we see that a logical model of the underground test monitoring process (m) can be expressed as a function of frequency (f) as

$$M(f) = S(f,W) \cdot P(R,f) \cdot N^{-1}(f) \cdot I(f) \cdot T(f) \cdot U(f) \quad (1)$$

where

S is the source function

W is the explosive yield

P is the path function

R is the distance from the source to the monitoring site

N is the site noise function

I is the measurement efficiency

T is the data transmission efficiency

U is the data use efficiency

and the importance of various values of R depend on the deployed sensor spacing.

Indeed, expression (1) is a very general model of the monitoring process, with complete representations of the process, either theoretical or empirical, requiring adequate models of each function. However, since monitoring by seismic techniques uses information on mechanical processes only (i.e., for seismology only U_m is non-zero in (1)), expression (1) may be replaced by

$$M_s(f) = S_m(f, W) \cdot P_m(R, f) \cdot N_m^{-1}(f) \cdot I_m(f) \cdot T(f) \cdot U_m(f) \quad (2)$$

where M_s represents monitoring by seismic techniques and the subscript, m , represents the mechanical components. Thus, representation of the seismic monitoring process requires only that (2), and not (1), be considered.

Each function of expression (2) depends on factors that are independent of the other functions; and, therefore can be modeled separately. In particular, the only effect on the monitoring process of considering cavity decoupling is that the mechanical source function $S_m(f, W, r)$ can be reduced by large factors (that are a function of the cavity radius, r) over the comparable source function $S_m(f, W, 0)$ for a tamped explosion (that is $r = 0$) of the same yield. These reduction factors are called decoupling factors and are frequency dependent (Springer et al, 1968; Seismore et al, 1969). In addition, while the nuclear and chemical explosive processes themselves are admittedly grossly different, if the mechanical source is defined as a boundary in the surrounding media (Figure 1), then the modeling of the NE monitoring process with HE sources results in merely replacing the nuclear mechanical source conditions, $NE S_m(f, W)$, with the high explosive mechanical source condition $HE S_m(f, W)$ at that source boundary. Thus, modeling of the monitoring process depends on the similarities of the source conditions; while discrimination between the source types depends on the differences between the source conditions.

Also, we should like to discuss the concept of Effective Yield Reduction and its relation to decoupling factors. Consider the case where two explosions of the same geometry occur at the same depth in the same media. The only difference is that the yields of the two explosions are

related by

$$W_2 = \frac{1}{64} W_1 \quad (3)$$

and thus explosion W_2 has a yield reduction of 64 when compared to W_1 . We approximate the source function of the large explosion by

$$S_m(f, W_1) = \begin{cases} K & \text{for } f \leq f_c \\ K \left(\frac{f_c}{f}\right)^2 & \text{for } f > f_c \end{cases} \quad (4)$$

where f_c is the corner frequency and K is a constant. We then apply simple yield scaling to relation (4) to find

$$S_m(f, W_2) = \begin{cases} \frac{K}{64} & \text{for } f \leq 4 f_c \\ \frac{K}{64} \left(\frac{4f_c}{f}\right)^2 & \text{for } f > 4 f_c \end{cases} \quad (5)$$

for the same source function of the small explosion. The ratio of the two source functions is then

$$\frac{S_m(f, W_2)}{S_m(f, W_1)} = \begin{cases} \frac{1}{64} & \text{for } f \leq f_c \\ \frac{1}{64} \left(\frac{f_c}{f}\right)^{-2} & \text{for } f_c \leq f \leq 4f_c \\ \frac{1}{4} & \text{for } f > 4f_c \end{cases} \quad (6)$$

which is also frequency dependent. In fact, the effects on the mechanical source function of detonating an explosion in a large cavity can be quite comparable to the effect of a large reduction in explosive yield. Thus, cavity decoupling of a nuclear explosion can be thought of as an effective, as opposed to actual, yield reduction when mechanical effects are considered. Combination of the monitoring model, expression (2), with the effective yield reduction concept, expression (6), indicates that a tamped high explosive charge may be a useful surrogate source to provide mechanical effects data associated with a much larger nuclear charge that is decoupled.

b. Basic Test Program Objectives. We suggest that a dedicated experimental program of at least three tamped, high-explosive detonations be planned and reviewed in support of Comprehensive Test Ban Treaty monitoring research. Conceptually, three HE charges would be detonated and measured in a manner to make effective use of the SALMON (Werth and Randolph, 1966, and many others) and STERLING (Seismore et al., 1969; Springer, et al., 1968; Perret, 1968A) nuclear explosion data base for tamped and decoupled events. Tentatively, the yields of the HE charges would be 5 tons, 40 tons, and 220 tons TNT equivalent. From this program, extensive mechanical data could be gained to address the principle objectives of evaluating a) simple yield scaling for large constant depth-of-burst charges in salt; b) the mechanical equivalence between a decoupled NE source and a tamped HE source; c) the mechanical equivalence between a tamped NE source and a tamped HE source, and thus d) the usefulness of HE tests as a CTB monitoring research tool. In the discussion of these objectives, we will rely heavily on the STERLING HE (Perret, 1968A; Springer, et al., 1968; and Seismore et al., 1969) data to illustrate both the potential of HE tests and the inadequacies in the data to be addressed in the conceptual program.

(1) The objective of evaluating simple (or cube root) yield scaling at a constant depth of burst in salt for large explosive events is extremely useful to the other objectives of the test program. Almost all data interpretation involved with accomplishing the other objectives of the test program will hinge on data scaling; and, therefore, the test program should provide confidence for those scaling laws. Indeed Trulio's extensive analysis and comparisons between COWBOY and SALMON (Trulio, 1978) seem to indicate that major deviations from simple scaling should not occur for explosions in salt, and this experimental program should finally confirm those results at large scale. While seismic observation, in fact, does not directly support simple yield scaling for underground nuclear detonations (Murphy, 1977), a seismic source model consistent with those observations (Muller and Murphy, 1971) attribute the deviations from that scaling to variations in depth-of-burst. We thus assume that simple scaling will hold for the HE sources, but the test program itself should finally verify that assumption for large yields.

(2) The objective of evaluating the mechanical equivalence between a decoupled NE source and a tamped HE source becomes particularly significant when evasion of a Comprehensive Test Ban Treaty by cavity decoupling is considered. This significance arises because such a comparison is both very useful to investigate, by full scale experimentation, CTB monitoring problems associated with evasion by cavity decoupling and necessary for research into the ability to discriminate between tamped HE and decoupled NE sources on the basis of mechanical data. As will be discussed later, it is the consideration of the effects of decoupling that provides the technical motivation for the selected explosive yields.

In this regard, the STERLING/STERLING HE data base provides a totally unique opportunity to make direct empirical comparisons using both seismic and source region data. From this data, both deep source region measurements (Perret, 1968A; Seismore, et al, 1969) and local seismic measurements (Springer, et al, 1968) tend to indicate that the two events were comparable below about 14 hertz but probably began to differ significantly (more than a factor of two) above 14 hertz. In particular, we note that the seismic data, except for one station, was quite comparable below 8 hertz between the 2.7 ton TNT equivalent STERLING HE and the .38 KT nuclear decoupled STERLING events (Springer et al, 1968). However, visual comparison of STERLING/STERLING HE spectra, presented by Springer, et al, do indicate lower amplitudes for the HE event relative to the nuclear event which becomes noticeable above 14 hertz.

The very limited, deep-source-region measurements (Seismore et al, 1969, Perret, 1968A) also seem to indicate a similar trend, although this indication is very tentative. Specifically a spectral ratio (Figure 2) was obtained from the one comparison made by Seismore et al by digitizing the Reduced Displacement Potentials in that article. (Private communication with J. R. Murphy of Systems, Science and Software.) This tentative analysis indicates that the corner frequency for the HE event (f_c^{HE}) was

approximately 10 hertz while the STERLING corner frequency (f_c) was at least 30 hertz. As a result, the HE amplitudes would become significantly lower than the decoupled nuclear source above 14 hertz.

Thus, on this basis, we tentatively conclude that the mechanical signal from the STERLING HE event was similar below the HE corner frequency and that the differences were a result of a significantly higher corner frequency for the STERLING nuclear event. This difference, if simple scaling and the source model of relation (4) applies, would result in an HE source of $\frac{1}{140}$ the yield of a decoupled nuclear event being significantly lower in amplitude only above about

$$10 \text{ hz/KT}^{1/3} \quad (7)$$

where the yield of expression (7) is the decoupled nuclear yield. From these relations we construct the following table to describe the approximation of a decoupled nuclear source with a tamped HE source.

TABLE I DECOUPLED NE/TAMPED HE RELATIONS

<u>Decoupled Nuclear Yield</u>	<u>Tamped High Explosive Yield</u>	<u>HE Significantly Lower Above</u>
1 KT	7 Tons	10 hz
5 KT	35 Tons	6 hz
10 KT	72 Tons	5 hz
20 KT	143 Tons	4 hz
40 KT	285 Tons	3 hz

When these frequencies are compared to the optimum detection frequencies that result from simple monitoring models (see Appendix B for example), one finds that they may be very comparable over much of the range important

to regional seismic monitoring. Thus the HE approximation of the decoupled nuclear source may be a useful approximation for CTB monitoring studies. Along this line, however, we find an apparent conflict between the 10 hertz corner frequency that we just suggested for STERLING HE and the conclusion that Trulio reached that spectra of data from the COWBOY tamped high explosive events, if simply scaled, were similar to spectra from the SALMON nuclear event (Trulio, 1978). The SALMON, and scaled COWBOY data, had a corner frequency near 3 hertz; however, scaling the STERLING HE data to a similar level would result in a corner frequency near 1 Hertz. Admittedly this analysis of STERLING HE was very preliminary and based on minimal data; however, this factor of 3 difference in corner frequency is hard to explain away by the crudeness alone and must remain as an apparent conflict at this time, which needs to be resolved.

We note that this entire discussion is based on limited data from a few experiments. In addition, these experiments are one to two orders of magnitude smaller than the yields in Table I. Thus, while indications of similarities and differences do exist, minimal confidence can be placed either in the quantitative statements or the importance attached to those statements. It is this lack of mechanical effects data in the effective yield range of 0.1 KT underground events that would be addressed during the test program.

(3) The objective of evaluating the equivalence between tamped NE and HE sources has long been suggested and is even more important today. The reason for this importance is that the HE source, because of both environmental and political limitations to NE sources, is simply a more versatile tool to investigate the seismic propagation problems of interest to monitoring a CTB with national seismic stations. For, while NE sources controlled by the United States are limited to the Nevada Test Site and the propagation paths that originate there, HE sources have the potential of being used with vastly different propagation paths elsewhere in the United States.

The SALMON event provides an excellent opportunity to evaluate in detail NE/HE underground equivalences as Trulio has already recognized (Trulio, 1978). It was a seismic experiment in a homogeneous salt medium,

with extensive measurements both in the immediate source region and at surface ground zero (Perret, 19688; Eisler and Hoffman, 1969) and extensive seismic experimentation (Springer, 1966; Jordan et al, 1966; and Archambeau et al, 1966 for examples). Thus the NE data base is guaranteed and already extensively analyzed. In addition, Trulio has already accomplished extensive studies in comparing the equivalence between COWBOY and SALMON, but this comparison extends over a data gap of three orders of magnitude in yield range (and we must again point to the apparent conflict in frequency characteristics we reach when we scale STERLING HE over a similar yield range).

The conceptual HE test program would provide an opportunity to bridge this data gap experimentally and obtain a set of subsurface, surface, and seismic data similar to the SALMON data set. Indeed, with the scaling finally confirmed by the experiments themselves, the data gained from the largest experiment would be very comparable to, and potentially supplement, the SALMON regional data.

(4) From the preceding three objectives, then, a clearer picture could be gained of the usefulness of tamped HE charges to approximate the mechanical effects from both decoupled and tamped nuclear explosion sources. Already this approximation appears useful on the basis of SALMON/STERLING/STERLING HE/COWBOY data, but that data is separated by a three order of magnitude gap that becomes critical, at full scale, when the implications of evasion by cavity decoupling are considered (Figure 3). The test program, then, would be specifically designed to fill in that magnitude gap, providing full scale mechanical effects data in a range of interest to monitoring a CTBT. After this extension, sound decisions can be made as to the future direction of HE experimentation, either tamped and/or decoupled, in support of CTB monitoring research. For example, one potential follow-on test series could provide for a significant variation in seismic paths providing yet another empirical test of the CTB monitoring process. A second example would be additional decoupling simulation experiments in the cavity(s) created during the proposed test program.

(5) In addition to these principle objectives, this experimental program can contribute both a focus and vital data for a) basic research in source region effects that are important to both CTB and Threshold Test Ban Treaty (TTBT) concerns, b) basic research in regional seismology, and c) systems evaluations of various CTBT monitoring concepts. Principal among these additional purposes would be clear documentation of the strong anelastic attenuation in the assumed "elastic" source region that Trullio (1978) has described. In particular, this additional attenuation may account for reductions in decoupling factors, from those predicted by elastic theory, and contributes to making quantitative application of present theoretical predictions a dubious procedure. Thus the effective yield reduction of 70, as compared with larger factors predicted by theory, may be the maximum attainable decoupling effect in salt. Also, these experiments would contribute data related to the development and effects of spall of the earth's surface at surface ground zero. In fact, these experiments may be uniquely suited for spall studies because, based on SALMON and limited STERLING data, the smallest event would probably not spall the ground surface, the largest event should spall the surface, and the intermediate event would be hard to predict. Thus spall, and the observable effects of spall, would be well tested. The regional seismological studies can be divided into investigations of 1) the development, dominance, and attenuation of various regional compressional phases (Rodean, 1979; Murphy, Appendix A) and thus the ability to detect and locate small seismic events, 2) the propagation of other regional phases such as L_g and their usefulness for seismic source discrimination, 3) studies of advantageous propagation anomalies and 4) propagation and detection of mechanical signals in other media. None of these studies require dedicated experiments; but all could be supported by such experimentation. Finally, the experiments, by producing a broad range of amplitudes in mechanical effects that span levels of interest to CTBT monitoring against evasion by decoupling, would provide a useful testbed for, and stimulus of, various monitoring techniques.

c. Location. At first glance the most ideal location for the test program would be the Tatum Salt Dome in southern Mississippi. This location would provide for the most direct source region comparisons between the available NE data base and the proposed HE tests, and the seismic data from the nuclear events is only directly applicable to the propagation paths emanating from that salt dome. In addition, the data from the extensive site investigations made in preparation for the nuclear events would be available to this test program.

However, several disadvantages also accompany the Tatum Salt Dome. First, we recognize that environmental and political concerns, because of the radiation from the nuclear tests, do exist. Second, because the top of the salt dome is over 500 m deep, and the nuclear events were located at 830 m depth, significantly shallower HE detonations, potentially desirable in this program or subsequent experiments, are not feasible at this site. Finally, the seismic propagation paths and receiver site noise characteristics may not really be optimum from the Tatum Dome. Indeed, since the seismic propagation data from that location do exist, this HE test program may provide a valuable opportunity to gain propagation data along different paths than SALMON.

In view of the disadvantages, then, we should consider the impact of selecting an alternate test site location. If the site were selected to assure that high quality salt could be found at the same overburden stress as SALMON and the SALMON source region instruments, then the source region measurements would still be comparable to SALMON/STERLING/STERLING HE. Thus the source region data would still permit the accomplishment of the principal objectives. Also, because of the ability to select more optimum test site locations, many of the secondary objectives may be significantly enhanced. Thus choice of a test site location other than the Tatum Salt Dome may be technically acceptable, because all objectives could still be accomplished although less directly, and may even provide long term benefits. Such alternate locations may be found in the Salt Domes in the northern parts of Louisiana or eastern Texas, or possibly even the salt beds of Kansas or New York (Fryklund, 1977).

d. Basic Measurement Plan. The measurement requirements can be divided into deep motion measurements near the source, surface ground-zero motion measurements, and off-site seismic experimentation. Of these, the deep motion measurements provide the most direct and unambiguous measure of the mechanical effects in the source region; and, since source equivalences are the principle objectives of this experimental program, they are the highest priority measurements. A minimal deep instrument array would be three instrumentation holes extending to one km depth, with at least three instruments, each recording three components of motion, per hole. This array should be planned to be used on all three events, so that sufficient dynamic range should be provided to record accurately the motion from all events. This requirement could be accomplished either by single sensors of sufficient dynamic range, or by dual sensors and remote switching. Within this scope, the detailed specifications of the instrument array can be determined later.

The off-site seismic measurement program can also contribute, but less directly, to the principle objectives of the program, and provides for the complete modeling of the monitoring process. In fact, the combination of source type, propagation path characteristics, and noise environments for this test program should be planned to provide a reasonable full-scale approximation to the CTBT monitoring problem when considering mechanical effects. For the basic program we would anticipate upgrading the 11 existing SDCS units, deployment of available (to be determined) National Seismic Station models, available contractor units, and an active volunteer program. Deployment would be (1) along at least three radial lines to a range of at least 10° for the larger shots; (2) at transition ranges of various crustal compressional phases; (3) at close-in stations for all shots; and (4) at geologic anomalies that may provide particular monitoring opportunities. Detailed experimentation and deployment planning should be developed during the planning process.

The near-surface, ground-zero motion measurements would support additional comparisons with SALMON, fill in for STERLING/STERLING HE data, provide an economic data control on analytic studies of the source region,

and support spall and source region attenuation studies. We would suggest at least 51 channels of data per event for these measurements, monitoring both surface and near-surface motions from near ground-zero to a range of 800 m. The 51 channels would allow for three component data to be obtained at two depths for each of six ranges along a main gauge line, and measurement at five supplementary locations along a secondary gauge line.

e. Data Analysis. Only limited data analysis, sufficient to accomplish the principal objectives and to report, in a reasonable manner, the results of the experimentation would be supported in the basic program. This analysis can be divided into source region studies and experimentation reports. Obviously, additional analysis would either be supported outside the program or delayed until support was desirable. The function of the basic experimental program, then, is data generation and observation reporting.

The plan to analyze the data should be formulated with the assistance of a scientific advisory committee established as early as possible to participate in experiment planning. This team should have qualified scientists, some of which would later become the principal scientists for the individual technical areas to be addressed. The entire committee should function throughout the program, on a periodic basis, to review objectives, ensure those objectives are being met, provide for prompt technical reviews, and ensure responsible reporting.

A data management and control plan should be established early in the program to provide for final planning of experimentation and efficient transfer and processing of both relevant historical data and experimental data generated during this program. In particular, the historical data could be used to practice data transfer procedures to ensure prompt data analysis during actual experimentation.

The source region studies will be absolutely essential to the evaluation of scaling laws, decoupled NE/tamped HE equivalence, tamped NE/HE equivalence, and simulation assessment. Since these issues are the central questions of the program, one principal scientist would be supported. This scientist would be a member of the advisory committee and have an established reputation in investigations of source region physics of underground

nuclear and high explosive sources. The scientist would be expected to provide a comprehensive technical report relating to the principal objectives and would be supported at a level to provide for a one-man staff.

The additional studies of anelastic attenuation in the source region, surface ground-zero spall effects, propagation of other regional phases, and identification of advantageous anomalies, should each have a principal scientist to analyze the data enough to report major results within each area, fit these results into the historical perspective, provide a reference guide to the data base, and prepare a technical report. These scientists would also be members of the advisory committee.

Finally, there would be one senior scientist responsible for overall analysis, interpretation, and reporting of the test program. This scientist would be responsible for providing a consolidated summary report of the overall test program and the principal results. As such, he would be a senior member of the Advisory Committee and be the scientist responsible for reporting to the Government.

f. Costs and Schedules. As this program is in the conceptual stage, detailed costs are not yet developed or fully warranted. We would suggest that these be prepared as a part of the planning. We provide here a general estimate of a reasonable schedule which allows one year for program consideration, a second year for preparation, test events in the first part of the third year, and analysis reporting in the remainder of the third year.

The major components of cost are planning, mobilization and test site operations; high explosive charge costs; deep motion experimentation; surface ground zero experimentation; seismic experimentation; and data analysis. A summary of these estimated costs follows:

TABLE II BASIC PROGRAM COSTS

	Year		
	1	2	3
Planning, Mobilization, and Site Operations	100	1400	1000
High Explosive Charge Costs		450	450
Deep Motion Experiments		900	300
Surface Motion Experiments		150	150
Seismic Experimentation		500	450
Data Analysis	50	200	400
	<u>150</u>	<u>3600</u>	<u>2750</u>

The total estimated cost is \$6.5 million in present dollars. The planning, mobilization, and site operations cost estimate is based on the costs incurred during Phase II of MISERS BLUFF (private communication with Lt Col Bestgen of the Defense Nuclear Agency), a surface HE test program of similar scope accomplished during the summer of 1978. The high explosive charge costs include the cost of drilling and cavity construction in addition to actual explosive costs. The deep motion estimate is a verbal estimate we recently received (personal communication with Coye Vincent from Physics Applications Inc.). The seismic experiment estimate is based on items from a similar program; and the data analysis is based on part-time participation only, by the required project scientists.

g. Possible Enhancements.

(1) Experimentation. An enhanced experimental program could contain two additional charges, each of 40 tons TNT equivalent, to investigate the effect of varying charge depth on the explosive source. Presently, one model of the nuclear source function (Mueller and Murphy, 1971) indicates that the seismic source for a shallow explosion is stronger, because of reduced overburden containment, than a deeper equivalent explosion. This effect would be investigated under the enhanced experimentation; however, the Tatum Salt Dome, because of the 500 m depth to the top of the dome, would not necessarily allow a large enough variation in depth. Thus should the Tatum Salt Dome not be available, or the enhanced experimental program be desired, a salt dome with a significantly shallower top should be used.

The enhanced experimentation would increase the length of deployment time for active experimentation in addition to adding 80 tons TNT equivalent requirement to charge costs. We estimate this addition would add ten percent to the program costs of the other program elements for a total increase of 600 thousand dollars in those costs, plus 200 thousand dollars increase in high explosive charge costs, for a total program cost increase of 800 thousand dollars incurred in the third year.

(2) Measurements. An enhanced measurement program could be divided into additional seismic measurements and/or additional deep source region

measurements. The additional seismic measurements would provide additional data on anelastic frequency attenuation rates that are important in estimating optimum detection frequencies as a function of distance (Rodean, 1979) for regional compressional phases. In particular, the Q^{-1} attenuation used by Rodean and Murphy may be too strong an attenuation operator. The additional deep source-region measurements would be contained in one additional deep instrument hole to investigate azimuthal variations of the source.

The impacts of each enhanced measurement set would only be within the experimental component of that enhancement. The seismic enhancement would consist of procurement and fielding of up to 10 additional Special Data Collection System units with KS36000 seismometers requiring 40 thousand dollars per unit in the second year for systems procurement and 40 thousand dollars per unit in the third year for deployment and operations. Total enhancement of this measurement program would thus add an estimated 800 thousand dollars to total program costs. The impact of one additional deep measurement hole is estimated to be 400 thousand dollars with 200 thousand dollars required in the second year and 200 thousand dollars in the third year.

(3) Analysis. Potential enhancements in the analysis program would include (a) increased support of the primary analysis objectives, (b) increased support of the secondary experimentation, and (c) evaluation of the prediction capabilities using first principal prediction procedures. The added support provided under enhanced analysis items (a) and (b) would support within the program a fuller analysis of the data particularly for enhanced measurements programs. Such enhancements would reasonably be a doubling of the basic levels. The evaluation of first principal predictions of the experiments would provide an assessment of present physical understanding of mechanical effects from underground explosive sources that would be important to confidence assessments of other theoretical predictions. Such an effort is expected to cost 100 thousand dollars in the second year for the predictions and 50 thousand dollars in the third year for the assessment of those predictions.

h. Potential Problem Areas. For the conceptual test program, either basic or enhanced, there exists five problem areas that need to be addressed early in the planning. These problem areas, in order of importance, are (1) test site selection/environmental impact studies associated with the HE detonations, (2) the effects of economic inflation on the program costs, (3) determination of cavity construction procedures for explosive charge emplacement, (4) selection of the high explosive charge material, and (5) achieving the dynamic range required for the source motion instrument array.

Alternatives in test site location and the environmental impact of those alternatives need to be defined as soon as possible to aid in final test planning and authorization activities. In particular, specific location alternatives, including Tatum Salt Dome, need to be defined to determine the trade-offs in experiment optimization, environmental constraints, and final program costs. This action is a Government action with support from at least one contractor requiring approximately 100K in first year planning costs.

The effects of economic inflation over the next few years will pose a problem. As has been indicated, the cost estimates are based on present costs or recent historical costs. The effects of inflation on program costs are illustrated in figure 4. We can see that high inflation rates will result in significant cost increases for any program. We therefore recommend that inflation be recognized in any budgets to be developed.

Problems 3 and 4 are related problems of charge design and emplacement procedures. The larger 320 ton charge requires cavity dimensions, for emplacement needs, that are on the order of several meters. Conventional overcoring procedures will not be suitable for these dimensions. At least two alternative procedures should be evaluated for constructing these large cavities (Rodean, 1971). One would be solution mining; the other would be explosive cavity construction. Solution mining should provide the best control on material disturbance and cavity size, but may be too expensive for a practical budget. Explosive cavity creation provides less control and more cavity disturbance but may be practical and economic. In addition, the experimentation and construction may be combined in the explosive cavity alternative. We, therefore, suggest that these alternatives be evaluated

during a small-scale explosive test program that is not included in this paper (private communication with Lt Col Bulin of DARPA/NMRO).

The last problem of providing sufficient dynamic range for the deep source-region measurements appears to be an engineering problem only. However, this question is of principle importance to the source measurements and, therefore, the means for providing this dynamic range should be determined as a part of the initial planning. Otherwise, the mechanical data may be compromised.

III. POTENTIAL ALTERNATIVES

In considering any program, one should always evaluate the advantages and disadvantages of potential alternatives. In considering this program, we shall evaluate alternatives as they relate to the problem of monitoring a Comprehensive Test Ban against evasion by cavity decoupling. There appears to be three broad categories of testing to be considered. These are (a) no dedicated testing, (b) dedicated nuclear tests, and (c) dedicated high explosive tests. Within the latter two categories, one should also consider tests in underground cavities and tests without the cavities.

a. No Dedicated Testing. One alternative to any program is simply not do any program. This alternative always has the advantage of minimizing the time and cost spent in implementing the tests and usually appears to be the cheapest alternative. However, when we are addressing new requirements for which no previous experience applies (such as imposed by the monitoring of a CTB against evasion) and when those requirements are of significant importance, we must determine how we can gain confidence in our ability to meet the new requirements. One way would be to extrapolate previous experience to the new situation. A second way would be to add on to other tests or normally occurring events. A third way would be to develop confidence, without additional experimentation, through analysis. Indeed, all of these approaches should be pursued prior to the implementation of the program discussed in this paper. However, the consideration (such as Appendix A, B, Rodean (1979), Bulin (1979), and others) has already begun to occur and preliminary indications lead to large uncertainties and little opportunistic experimentation when mechanical effects are considered.

b. Dedicated Nuclear Tests. Obviously, the most faithful representation of the decoupled nuclear source function is a nuclear detonation in a large cavity. However, we assume that future nuclear detonations are limited to the Nevada Test Site. Such tests cannot be conducted in a salt medium which is thought to be the most likely medium for cavity decoupling and the construction of large cavities in other media is either very expensive (Kipp and Kennedy, 1978) or infeasible. In addition, when one considers the monitoring problem (equation 2) he recognizes that even nuclear tests at the Nevada Test Site have the path model specified by such tests and even NTS tests with suitable source conditions are then merely an approximation to the practical problem. Thus the alternative of nuclear tests in a cavity is merely an approximation, is feasible only at very low yields and, even then, very expensive. We shall, therefore, not consider it further at this time.

One can also consider dedicated nuclear tests without the cavity to reduce the cost and eliminate feasibility concerns. To model the severe reduction in mechanical effects caused by the cavity, one would provide a corresponding reduction in nuclear yields and, applying a factor of 70 to multi-kiloton devices, would use nuclear yields on the order of 0.1 kiloton. Also one could accept simple-yield scaling and use SALMON/STERLING data to establish tamped/decoupled equivalence relations. However, this test program would still be restricted to paths coming out of NTS and is obviously still only a model of the monitoring problem. Further, although not considered in detail, we believe such a program would cost more than the program discussed in this paper. The program would probably not survive in a comparison with no dedicated testing because of the vast data base already available from the Nevada Test Site and/or the potential for add-on experimentation to other tests. However, when one considers other than mechanical effects, the apparent yield reduction does not occur, and then such a testing program may be required.

Dedicated High Explosive Tests. One could also accomplish HE testing in a salt cavity to investigate further the phenomena of decoupling. However, merely by accepting HE testing, one accepts a simulation of the

source function and opens the questions of the accuracy of the simulation. Indeed, crude simulation of the mechanical effects has been accomplished using high explosive charges (Herbst et al., 1961) and was the original basis for establishing the effectiveness of cavity decoupling (Latter, et al., 1961). However, the simulation in those experiments was indeed crude, and the direct application of the data is questionable. In addition, the use of high explosives in a cavity involves both the availability or construction of an appropriately-sized cavity and the development of simulation techniques. We assume these requirements presently limit such testing to small-scale during which only source phenomena can be investigated. Thus the complete monitoring problem is not represented, but only an approximation of the source physics. Nonetheless, such experimentation may be useful in the future to obtain a higher frequency source.

The final alternative is to use tamped HE sources to approximate the mechanical effects from cavity-decoupled nuclear detonations. The use of HE sources, as opposed to NE sources, eliminates the restriction of testing at the Nevada Test Site. Thus significant variations in path effects should be achievable by using path analogs that are available in the United States. Elimination of the cavity provides the programmatic advantages of eliminating the need to construct or find a large cavity and a major reduction in the amount of high explosive required to radiate a mechanical signal of a given level away from the source region.

The major question is, then, is the approximation good enough? The discussions of the STERLING/STERLING HE data indicate that there are differences in those two sources. However, when we compare these differences to the large factors associated with evasion by decoupling and the variations in decoupled sources that can result from changes in evasion practices, we conclude that the tamped high-explosive detonation may produce a useful mechanical approximation to the decoupled nuclear source. We thus recommend that tamped HE sources be investigated as a useful tool for full scale testing related to CTB monitoring systems. In this regard, we find a direct comparison to simulation of nuclear weapons effects on strategic structures,

and we paraphrase Port and Cooper (1979) as follows:

A purest desires a high-fidelity simulation as a matter of principle. On the other hand, a pragmatist recognizes that no simulation is perfect; and furthermore, under some circumstances either the conditions for a "perfect" simulation cannot be defined or the simulation test requirements are prohibitive. In addition, he notes that, if the monitoring system proves effective in "overtest" conditions, confidence would be assured and the entire question of test fidelity would be moot.

The tamped HE source is a monitoring conservative (overtest) approximation to the decoupled NE source because its lower frequency signals may provide less monitorable information. We thus recommend that tamped HE sources be investigated as a useful tool for full scale experimentation related to CTB monitoring systems.

IV SUMMARY AND CONCLUSIONS

When we consider the requirements for a complete, full-scale model of monitoring a Comprehensive Test Ban that might be evaded by cavity decoupling, we recognize that such a model is simply unachievable in the United States. However, on the basis of limited seismic data and extremely limited underground source-region data from the STERLING/STERLING HE experiments, we find that a useful approximation of the mechanical component of that problem may be achievable through the use of tamped high-explosive detonations. In particular, on the basis of the STERLING/STERLING HE experiments, the mechanical effects from multi-kiloton nuclear detonations that are decoupled should be approximated by tamped high explosive charges on the order of 100 tons. Data from such tests would be used to address both CTB detection and discrimination concerns.

We therefore recommend that an underground HE test program be planned and reviewed and, on the basis of that process, a decision made on implementation. The initial review of such a program, contained in this document, indicates that considerations should be directed toward a basic program tentatively consisting of 5 tons, 40 tons, and 320 tons of TNT

equivalent yields respectively. This program would generate extensive mechanical data from source region, surface ground zero, and seismic instruments to address the principle objectives of evaluating (a) simple yield scaling for constant depth-of-burst charges in salt at large scale; (b) the mechanical equivalence between a decoupled nuclear explosion and a tamped chemical explosion; (c) the mechanical equivalence between tamped nuclear and chemical explosions, and thus (d) the usefulness of HE tests as a CTB monitoring research tool. In order to provide for these objectives, the charges should be detonated as close as feasible to the conditions of the SALMON/STERLING nuclear detonations. In addition to the principle objectives, the experimental program should contribute both a focus and vital data for (a) basic research in source region effects, (b) basic research in regional seismology, and (c) systems evaluations of various monitoring techniques.

Enhancements to the basic program, in experimentation, measurements, and analysis should also be considered. The enhanced experimentation could include two 40 ton TNT equivalent charges detonated at shallower and deeper burial depths than the charge in the basic program to investigate the influence of burial depth on the mechanical effects. Enhancements in measurements would provide additional definition of the source region and/or additional data on the propagation characteristics of regional phases. The enhanced analysis program would provide for more than minimum analysis during the program and/or evaluation of prediction capabilities based on first principal physics.

A summary of tentative cost estimates is contained in Table III. We assume in this table that the shot dates are early in the third fiscal year and that the second fiscal year is used for preparation. The cost figures are based on the best available data from previous tests and are present dollar estimates. From this table we see that the basic program, which we consider an absolute minimum to accomplish the technical objectives, is estimated at 6.5 million dollars. We believe that a good experimental program would consist of the basic program plus enhanced experimentation and some enhanced measurements for an estimated cost of 8.1 million; and that a complete program would consist of all enhancements for a total of 9.25 million.

Five problem areas should be addressed during the planning of this program. These areas, in order of priority, are site selection/environmental concerns, economic inflation, explosive charge emplacement procedures, selection of the high explosive, and achievement of the dynamic range required for efficient source motion measurements. None of these problem areas affect the feasibility of the test program.

We therefore conclude that a tamped high explosive test program is feasible and can provide a useful representation of the mechanical effects from tamped/decoupled nuclear detonations. The high explosive source offers the advantages of flexibility in location, minimal environmental impact, and economy when compared to a nuclear source. It therefore appears to be a useful tool for research into Comprehensive Test Ban Monitoring techniques. We propose then, that detailed planning for such a test program be initiated as soon as possible to prepare for an intelligent program implementation decision. We suggest that the cost of this test program, designed to approximate a principle evasion scenario that could neutralize a monitoring effort, is modest compared to the cost of implementing that monitoring effort.

TABLE III

Estimated Program Costs - (FY 79 dollars)

<u>Program</u>	Cost (\$ thousands)		
	<u>First Year</u>	<u>Second Year</u>	<u>Third Year</u>
<u>Basic Program</u>			
Planning, Preparation and Site Operations	100	1400	1000
HE Costs		450	450
Deep Motions		900	300
Surface Motions		150	150
Seismic Exps		500	450
Data Analysis	50	200	400
	<u>150</u>	<u>3600</u>	<u>2750</u>
<u>Enhanced Experiments</u>			
Planning, Preparation and Site Operations			250
HE Costs			200
Deep Motions			130
Surface Motions			40
Seismic Motions			105
Data Analysis			75
			<u>800</u>
<u>Enhanced Measurements</u>			
Seismic Motions		400	400
Deep Motions		200	200
		<u>600</u>	<u>600</u>
<u>Enhanced Analysis</u>			
Data Analysis		200	400
Predictions		100	50
		<u>300</u>	<u>450</u>
<u>Totals</u>	150	4500	4600

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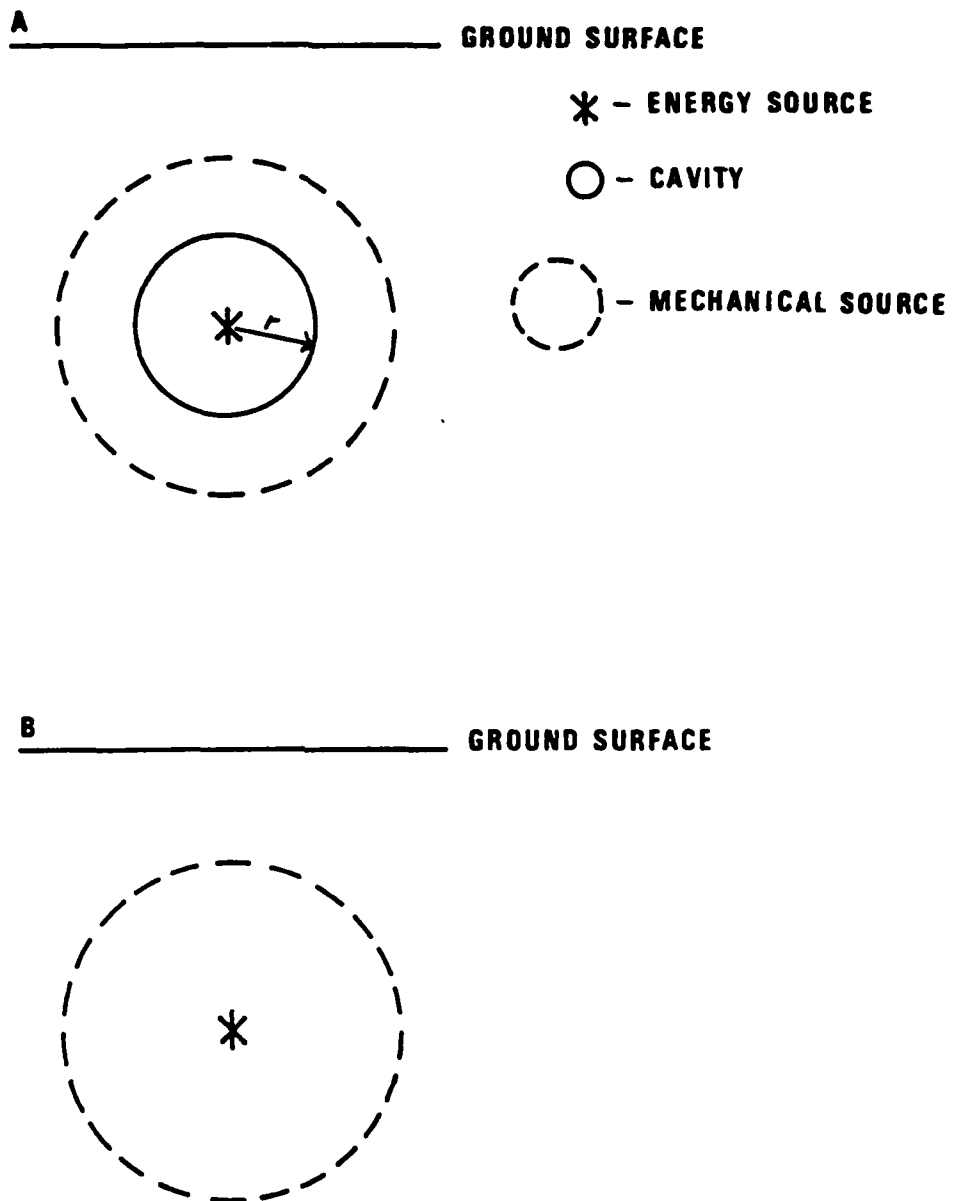


Figure 1. Schematic representations of the mechanical source boundary for (A) a nuclear energy source in a cavity of radius r and (b) a tamped high explosive energy source.

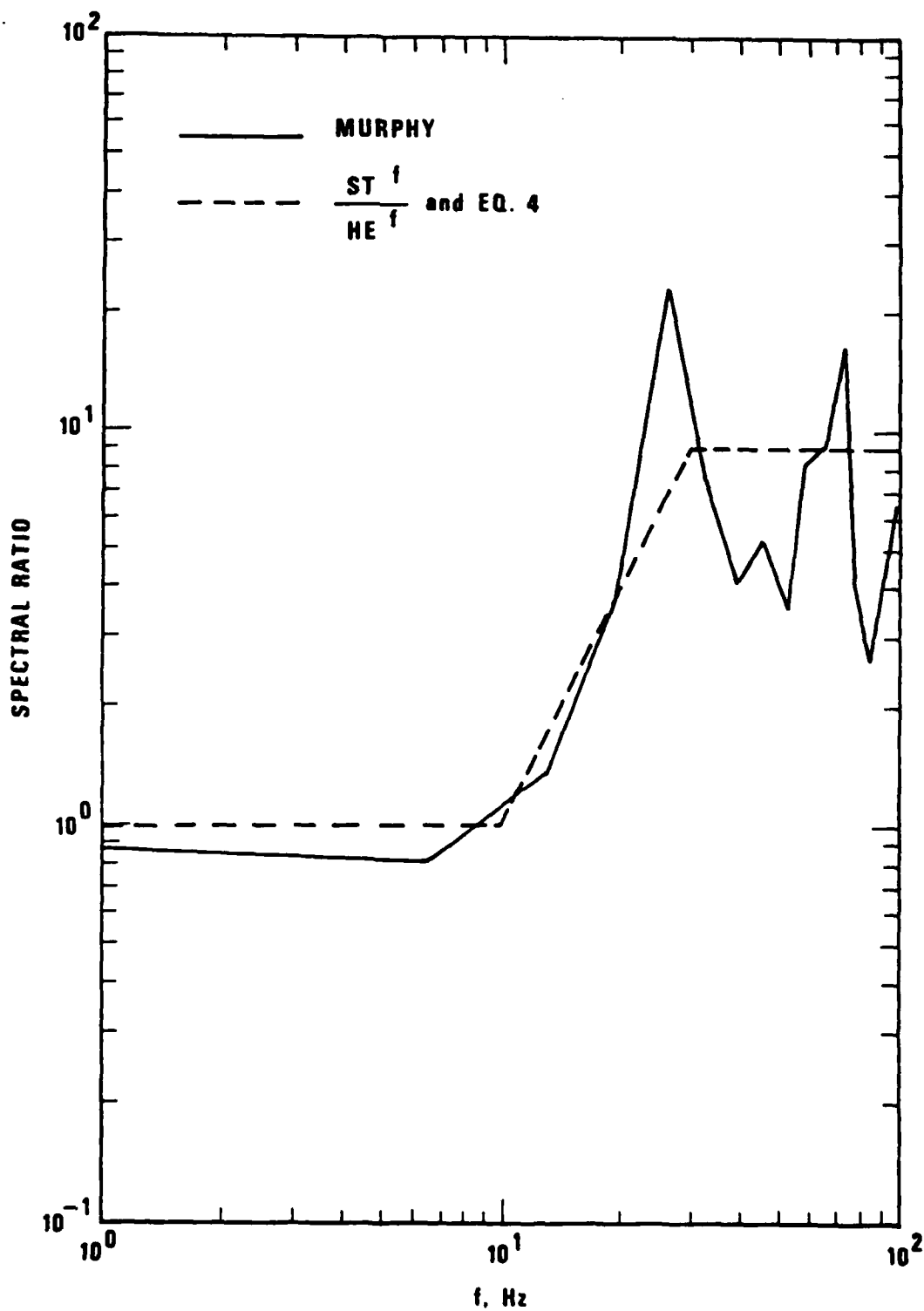


Figure 2. A tentative spectral ratio developed by Murphy from source region data from STERLING (ST) and STERLING HE. The dashed line represents the ratio obtained from equation 4 with a HE corner frequency of 10 hertz, a STERLING corner frequency of 30 hertz, and the same K for both events.

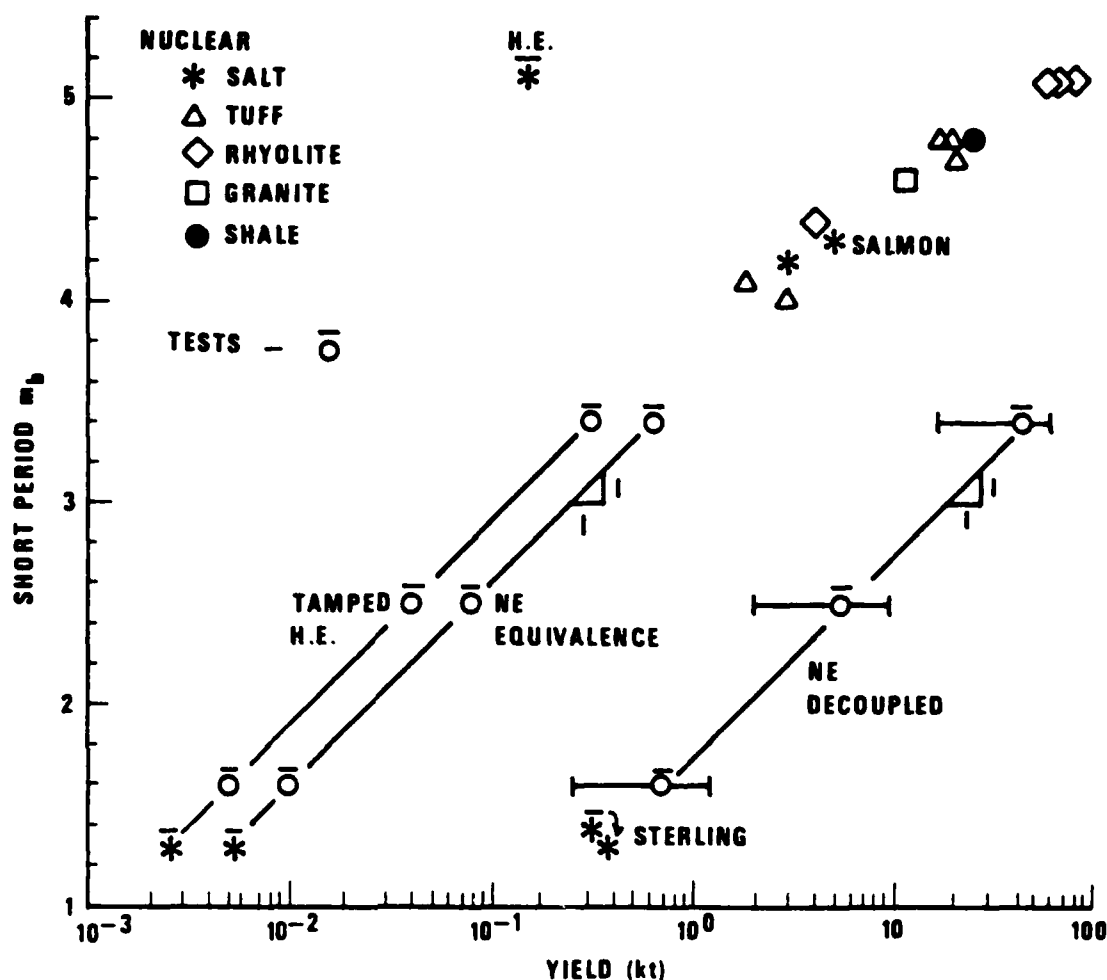


Figure 3. A short period (1 to 2 hz) representation of this conceptual test program in relation to other existing data. The nuclear data is a direct transfer from a similar plot by Rodean (Rodean, 1971). The STERLING HE data is assumed to have a magnitude similar to STERLING. The connecting lines with a 1 to 1 slope represent yield scaling. The tamped HE line extends from the TNT equivalent yield for STERLING HE. The NE equivalence line assumes a 2 to 1 NE/HE yield equivalence. The NE decoupled line is simple scaling of STERLING. The horizontal bounds on the decoupled line represent two different estimates of the effect of a mined vs explosive produced cavity (Bulin, 1979).

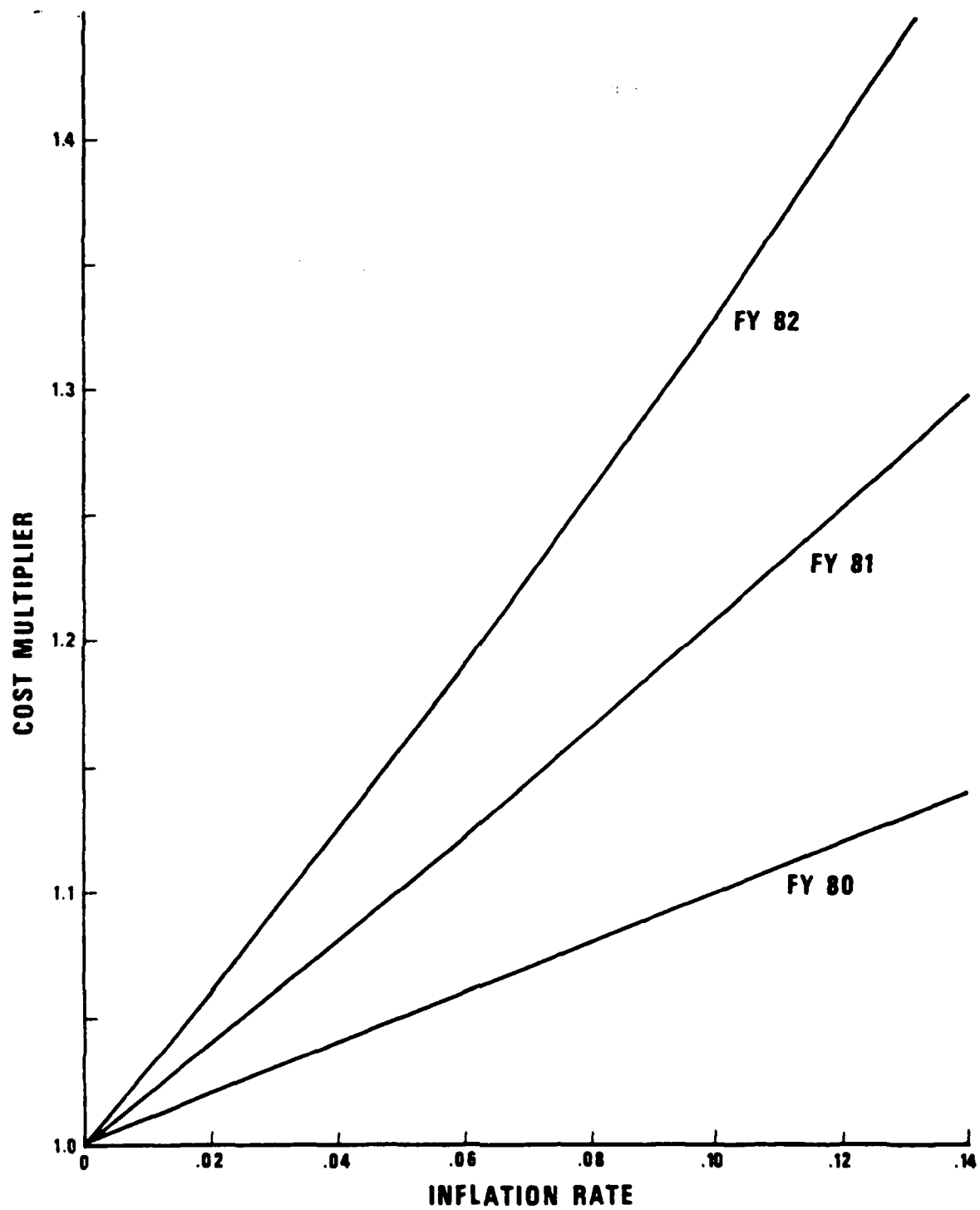


Figure 4. Program Cost Multiplier as a function of Inflation Rate

APPENDIX A

A BOUNDING ANALYSIS ON DECOUPLING

by

JOHN R. MURPHY

of

SYSTEMS, SCIENCE AND SOFTWARE



SYSTEMS, SCIENCE AND SOFTWARE

Date: 5/4/

Time:

ACTION:

To: Captain Mike Shore

From: John R. Murphy

Subject: A Bounding Analysis of the Factors Influencing the Detection of Decoupled Explosions at Regional Distances

At the February ARPA Conference on Decoupling, Rodean of LLL described a preliminary model he had put together to assess the detectability of crustal P phases from decoupled explosions at regional distances. The purpose of the analysis summarized in this memo has been to review the various assumptions implicit in Rodean's treatment of the problem and to propose reasonable optimistic and pessimistic alternatives to his assumptions for use as input to a set of bounding simulations. The factors influencing detectability may be listed as follows: (i) the seismic source function, (ii) propagation path effects, and (iii) seismic noise conditions at the recording site. Each of these factors is considered in turn in the discussion below.

For his decoupled source function, Rodean adopted the original Latter et al. (1961) low frequency approximation corresponding to a simple step in pressure on the cavity wall. That is, if W is the yield of an explosion in a cavity of radius r_c , then the seismic source function is assumed to be a step in pressure P , where

$$P = \frac{(\alpha-1) W}{\frac{4}{3} \pi r_c^3} \quad (1)$$

and α is the ratio of specific heats for air (≈ 1.2). Now, for such a source function, the far-field displacement spectrum is essentially flat (i.e. constant amplitude level) from DC up to a corner frequency $\omega_0 = c/r_c$ where r_c is the compressional wave velocity in the source medium. For purposes of his simulation, Rodean assumed that the spectrum was flat out to a

corner frequency of 20 Hz and for Salmon salt (i.e. $c = 4.55$ km/sec) this translates into a maximum cavity radius of about 34 m. Now, under the Patterson criterion (i.e. $P \leq \text{overburden pressure}$), such a cavity at Salmon shot depth will fully decouple an explosion with a yield of about 3.7 kt (i.e. $P = 180$ bars) and this is the upper limit of the yield considered in Rodean's analysis.

Our current understanding of decoupling suggests that the above model gives a minimum estimate of the seismic source function in that it ignores the high frequency enhancement introduced by the initial pressure spike on the wall and, in fact, tends to overestimate the observed decoupling even at low frequencies by a factor of two or more, at least for shot generated cavities. This is illustrated in Figure 1 where the observed Salmon/Sterling spectral ratio derived from seismic data is compared with the ratio of the observed Salmon source function (Springer et al., 1968) to the theoretical Sterling source function predicted by Rodean's model. It can be seen that Rodean's source model underestimates the strength of the Sterling source function by a factor of two or more across the frequency range from 1 to 20 Hz. Figure 2 shows a comparison of my estimates of the "minimum" and "maximum" seismic source functions for a fully decoupled 3.7 kt explosion in a 34 m radius cavity in salt at Salmon depth. The "minimum" estimate corresponds to Rodean's approximation to a simple 180 bar step in pressure. The "maximum" estimate incorporates a frequency-independent factor of two increase in amplitude level (to make the low frequency level consistent with observed Sterling data) as well as the high frequency effect of the initial 3.8 kilobar pressure spike on the cavity wall. It can be seen that at 20 Hz the amplitude level associated with this "maximum" estimate is more than a factor of five larger than that associated with Rodean's approximation.

The effect of the propagation path on the radiated signal can be separated into its elastic and inelastic components. Rodean assumed that the P wave transmission path could be approximated as an infinite, homogeneous fullspace, which is the simplest conceivable model. The inelastic attenuation along this path was modeled by the standard constant Q model so that the spectral amplitude level at distance R is given by

$$A(\omega) = \frac{\dot{\phi}(\omega)}{RC} e^{-\frac{\omega R}{2CQ}} \quad (2)$$

where $\dot{\phi}(\omega)$ denotes the reduced velocity potential corresponding to the selected seismic source function and Q is the dissipation term which Rodean estimated to lie in the range 420 to 700 for P wave propagation in stable continental interiors typified by the Eastern U. S. (EUS).

The greatest limitation of the propagation model described above lies in the assumption that the observed P wave of interest will be a direct arrival. In fact it is well documented that the P phases used in event location at regional distances are refracted arrivals which bottom at depth in the crust due to the general increase of velocity with depth. Figure 3 shows the travel path associated with one such phase. Now it can be shown (Murphy, 1972) that for this simple earth model the amplitude of the refracted P wave measured at the free surface will be given approximately by

$$A(\omega) \approx \frac{50 \dot{\phi}(\omega)}{\omega R^2 C} e^{-\frac{\omega R}{2CQ}} \quad (3)$$

for $\dot{\phi}(\omega)$ in m^3 , R in km, C in km/sec. Thus, the refracted P wave is predicted to decay as $1/R^2$ in the absence of inelastic attenuation as opposed to the direct P wave which is predicted to have an elastic decay rate of $1/R$. Figure 4 shows a comparison of the amplitude/distance curves predicted by equations (2) and (3) for 1 Hz P waves (Q=420) with the empirical fit to the EUS P wave data (dashed line) proposed by Evernden (1967).

It can be seen that equation (3) predicts results which agree reasonably well with the observed data while equation (2) significantly underestimates the observed attenuation with distance. Therefore, equation (3) will be used for purposes of the present simulation. In agreement with Rodean, a lower bound Q value of 420 will be adopted and this will be associated with the "minimum" source function (i.e. it will be assumed to give the lower bound to the signal strength at distance R). Specification of the upper bound for Q is more difficult. Rodean selected a value of 700 on the basis of his analyses of some published EUS peak amplitude attenuation results. However, at the Decoupling Conference in February, Nuttli reported Q values as large as 1500 for EUS observations in the frequency range from 1 to 10 Hz. Therefore, we will adopt a Q value of 1500 to be associated with the "maximum" source function (i.e. it will be assumed to give the upper bound to the signal strength at distance R).

The final factor influencing detectability is the noise background at the receiver site. Figure 5 shows a summary based on results published by Fix (1972) in conjunction with his analysis of the noise background at the Queen City, Arizona (QC-AZ) experimental site. Superimposed on the QC-AZ data are Fix's interpretation of Brune and Oliver's minimum and average noise levels in the 1 to 10 Hz frequency band. It can be seen that both the Brune and Oliver curves as well as the QC-AZ data indicate a $1/f^2$ decrease in noise level above about 3 Hz. However, while the Brune and Oliver generalizations continue this trend down to 1 Hz, the QC-AZ data indicate a relatively flat plateau between 1 and 3 Hz. It can be seen that Rodean's noise specification seems to be a fit to the low frequency QC-AZ data and consequently tends to underestimate even the minimum noise levels at high frequencies. As is indicated on the figure we have associated the noise parameterization

$$N(f) = \frac{2 \times 10^{-11}}{f^2} \text{ meters rms/milliHertz}$$

with the "maximum" source function as representative of the maximum signal to noise ratio to be expected at a very quiet site. A noise background a factor of three above this level has been selected as representative of somewhat poorer operating conditions (although still better than average) and associated with the "minimum" source function.

Before proceeding to the simulation of Rodean's scenario we will test the predictions of these models against Sterling. Figures 6 and 7 show the signal to noise (S/N) ratios predicted by Rodean's model and the "minimum" model (i.e. "minimum" source function, $Q=420$ in equation (3) and $N(f) = 6 \times 10^{-11}/f^2$ mrms/mHz) respectively.*

It can be seen that the Rodean model predicts S/N ratios which are greater than 1.0 out to ranges of 300 km for frequencies in the 5 to 20 Hz range. In fact, Sterling was not detected at ranges greater than 70 km and, consequently, Rodean's model provides a very optimistic view of detectability in this case. On the other hand, the "minimum" model (Figure 7) predicts Sterling S/N ratios of greater than 1.0 only out to about 60 km, in better agreement with the observations.

Figures 8-10 show the S/N ratios predicted by the "minimum," "maximum" and Rodean models respectively for a hypothetical 3.7 kt explosion in 34 m radius cavity in salt

*In modeling Sterling, using the "minimum" model it became apparent that the ω^{-1} decrease in signal strength predicted by equation (3) was not appropriate. This agrees with other observations that the predicted integration effect is very sensitive to the velocity structure at the depth at which the ray bottoms. Consequently, in computing the signal to noise ratio shown on this and the following figures, the amplitude has been normalized to the predicted 1 Hz level and the ω^{-1} dependence has been dropped.

at Salmon depth. It can be seen from a comparison of these figures that the Rodean model again provides an optimistic view of detectability. This is illustrated more clearly in Figures 11-14 where the S/N ratios predicted by the "minimum," "maximum" and Rodean models are compared separately for each of the four selected frequency components (i.e. 1, 5, 9 and 19 Hz). It can be seen that the Rodean model consistently provides S/N estimates which are even higher than those associated with the "maximum" P wave signal strength model. The explanation for this lies in the elastic propagation model selected by Rodean which assumes a nominal $1/R$ geometrical spreading for the P wave arrival. As was noted above, this is inappropriate for the P phases used in event location at regional distances and significantly underestimates the observed attenuation, even for paths in stable continental interiors (cf Figure 4), leading to an overly optimistic view of detectability.

With regard to the "minimum" and "maximum" S/N ratios shown on these figures, it can be seen that at a fixed S/N level the uncertainty in detectability varies from a factor of 2.5 to 4.0 in distance depending on the frequency. These, of course, correspond to average regional values and do not take into account uncertainties due to anomalous crustal structure or local site geology which may significantly perturb the amplitude level at a particular site.

In conclusion, even though the Rodean model incorporates a minimum level decoupled source function, this effect is more than offset by the optimistic propagation and noise models, producing estimates of detectability which appear to be much too optimistic for the P phases used in event location at regional distances. The results of the present simulations using the "minimum" and "maximum" bounding models again suggest that the maximum S/N for low yield decoupled events may well occur in the 10 to 20 Hz band out to ranges of 500 km or more. Although initial P wave arrivals are of primary concern with regard to event location, it should be noted that in the EUS the L_g phase is significantly larger than P even at ranges of

less than 100 km. Thus, since Lg attenuates less rapidly than P, it may be that single station P detection together with multiple station Lg detection could be used to lower the detection threshold. More work will be required to provide quantitative insight into this problem.

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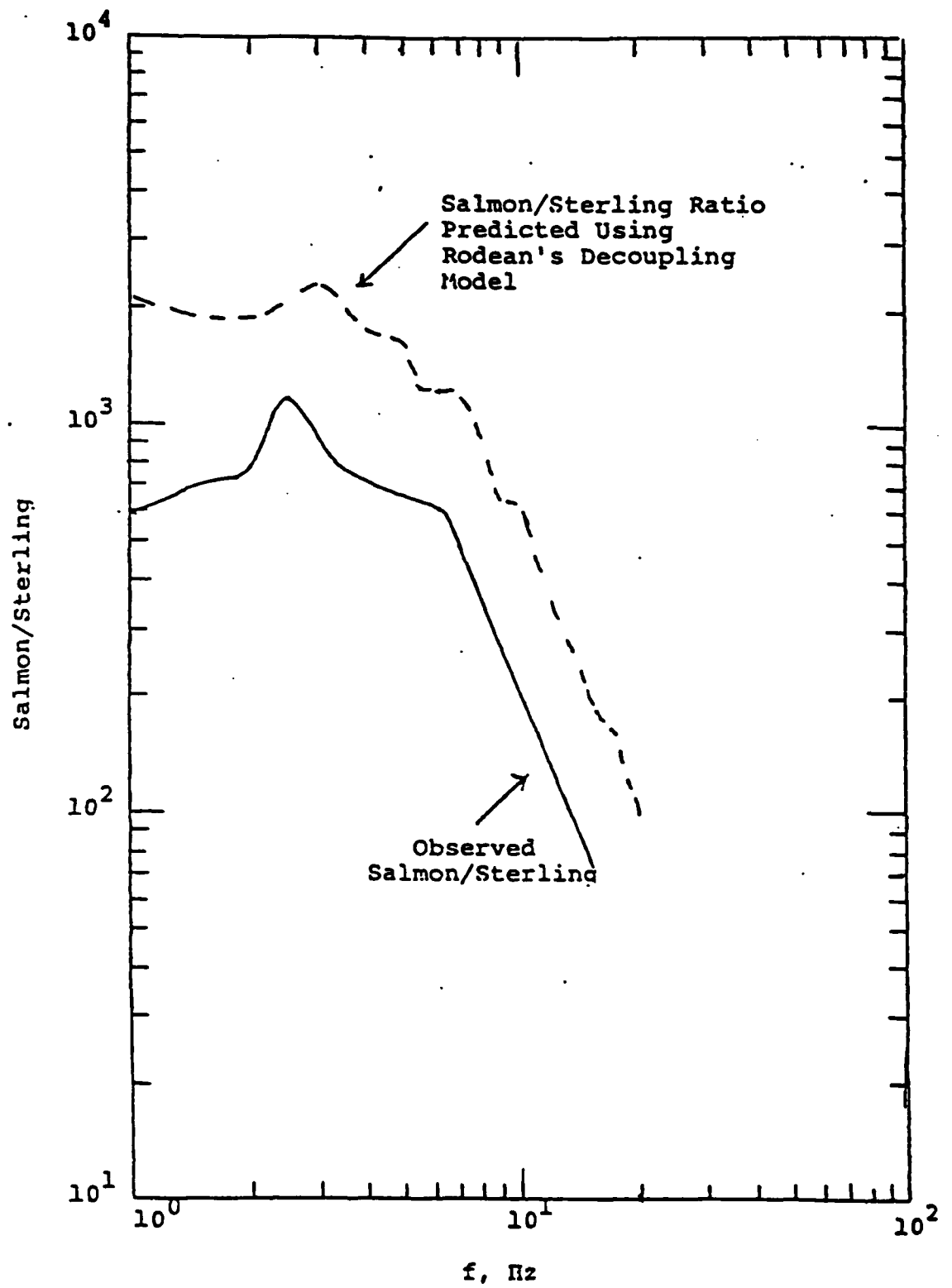


Figure 1. Comparison of Observed Salmon/Sterling Spectral Ratio with that Predicted by Rodean's Decoupling Model

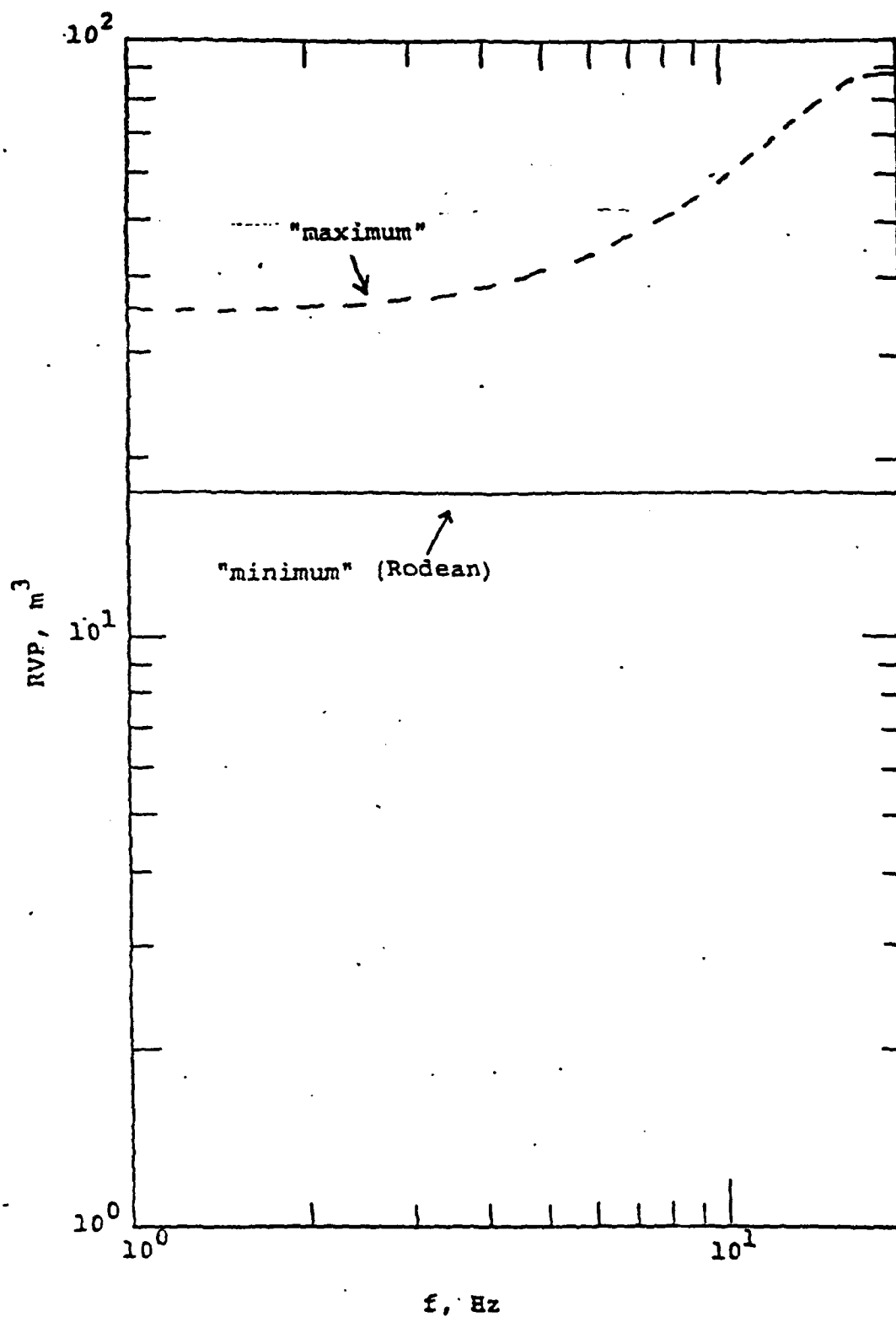


Figure 2. Decoupled Source Function Estimates:
3.7 kt in 34.m Radius
Cavity in Salmon Salt

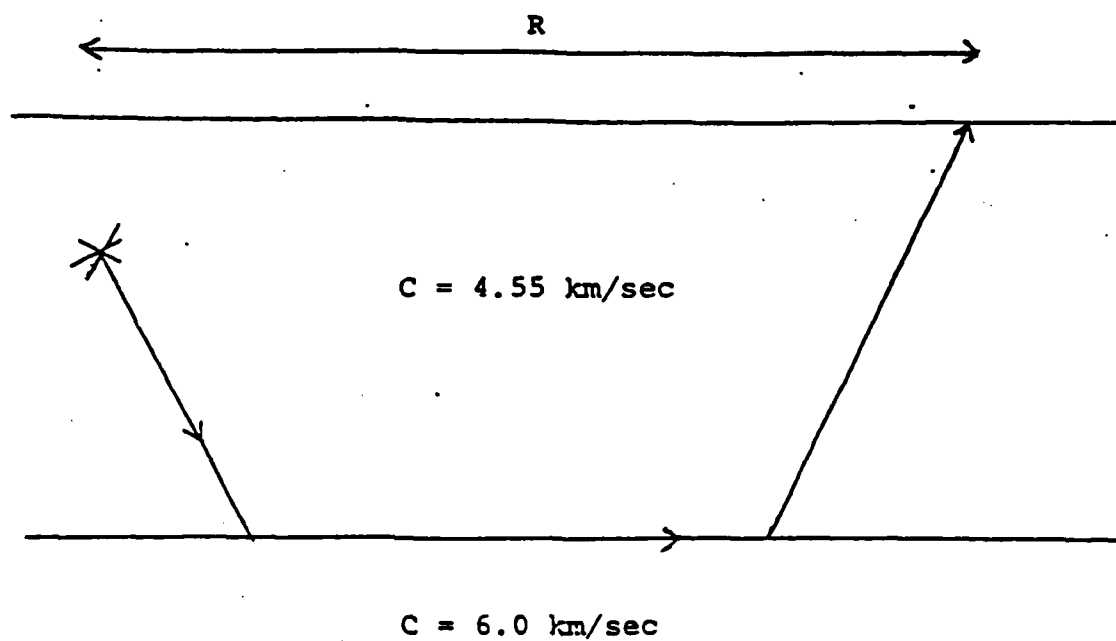


Figure 3. Propagation Path Model for Regional P Phase.

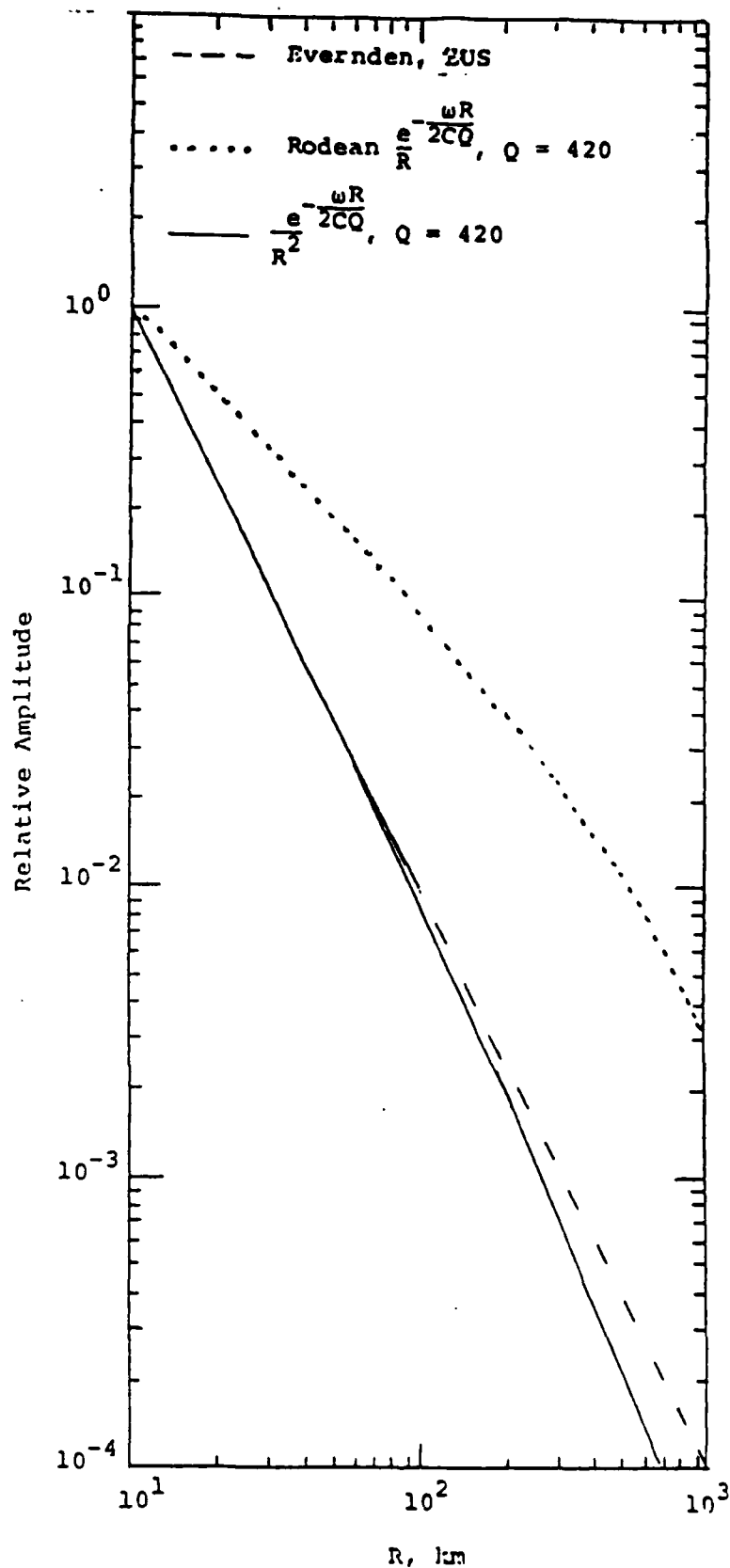


Figure 4. Comparison of Predicted and Observed, (dashed) P Wave Amplitude/Distance Curves

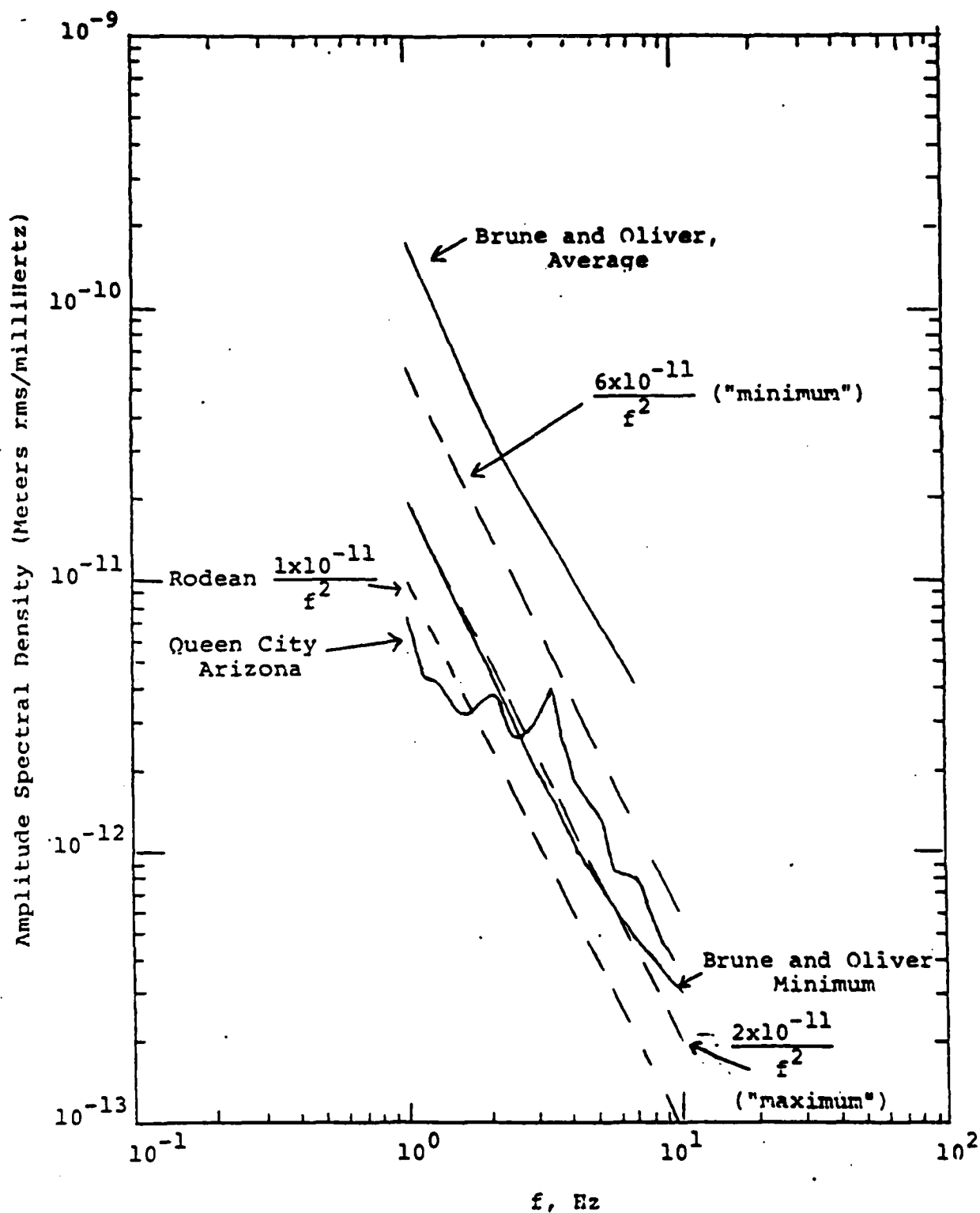


Figure 5. Comparison of Seismic Background Noise Estimates in the 1 to 10 Hz Frequency Band.

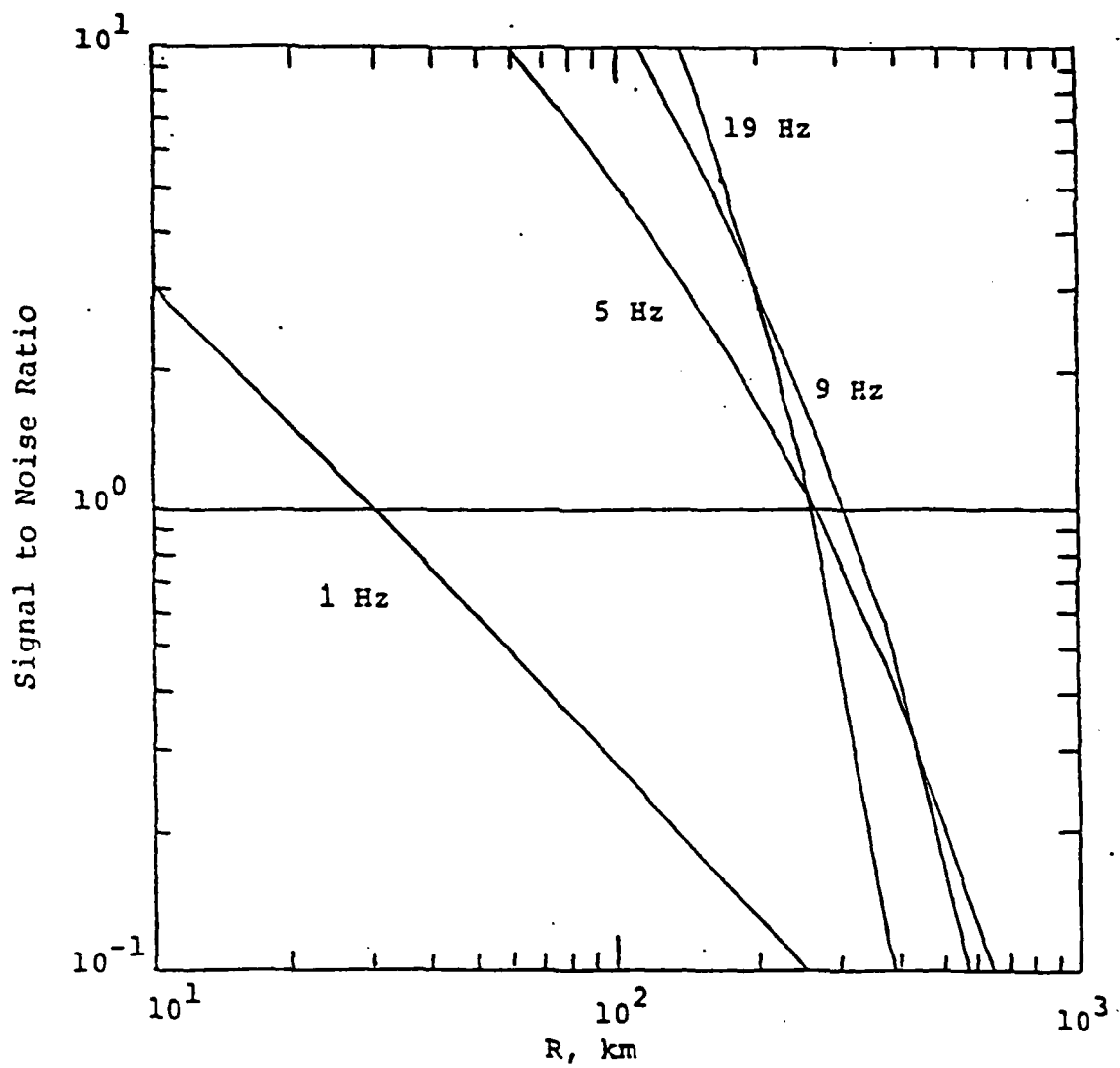


Figure 6. Sterling Detection Thresholds as a Function of Frequency Predicted by the Rodean Model.

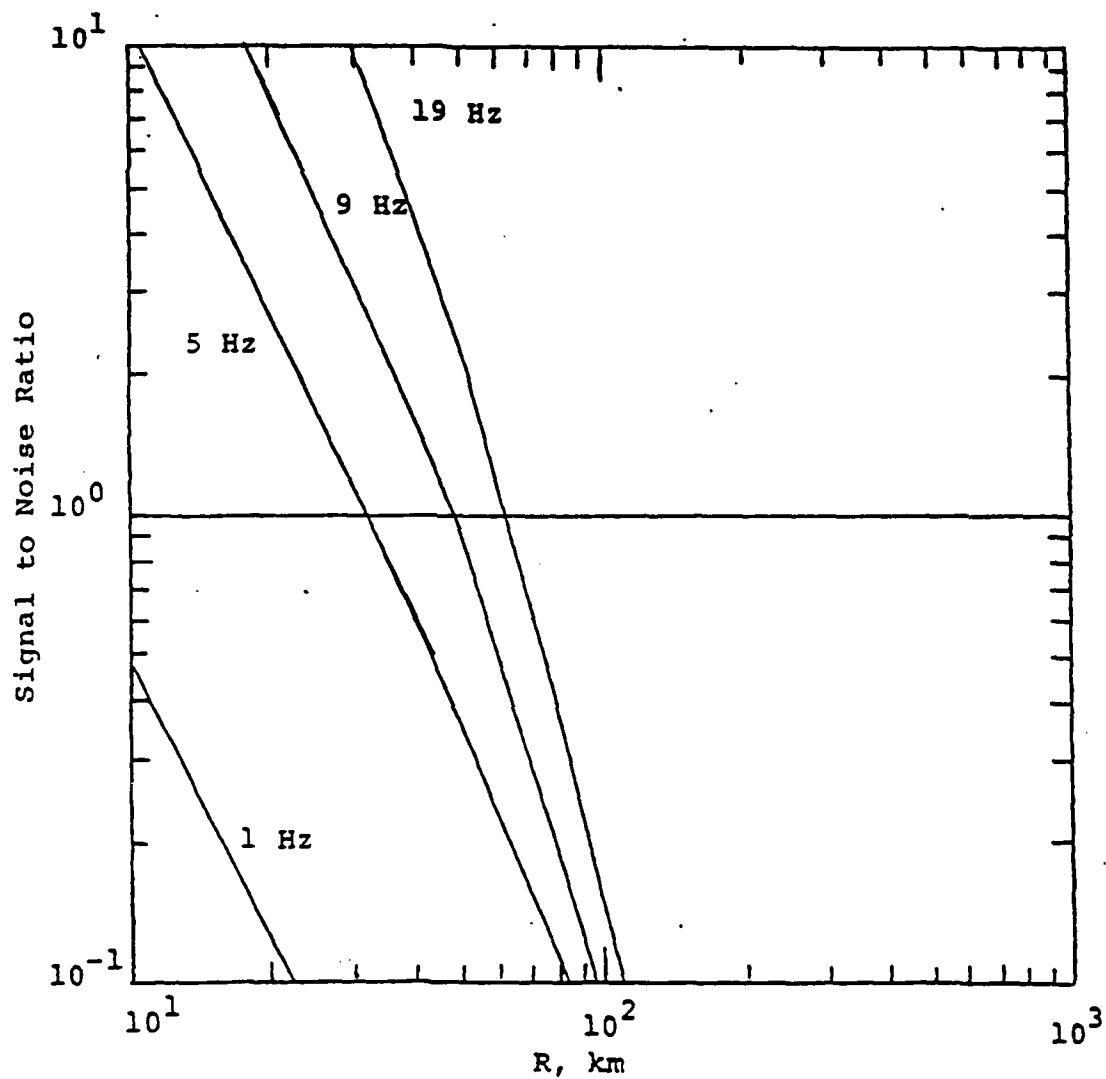


Figure 7. Sterling Detection Thresholds as a Function of Frequency Predicted by the "Minimum" Model.

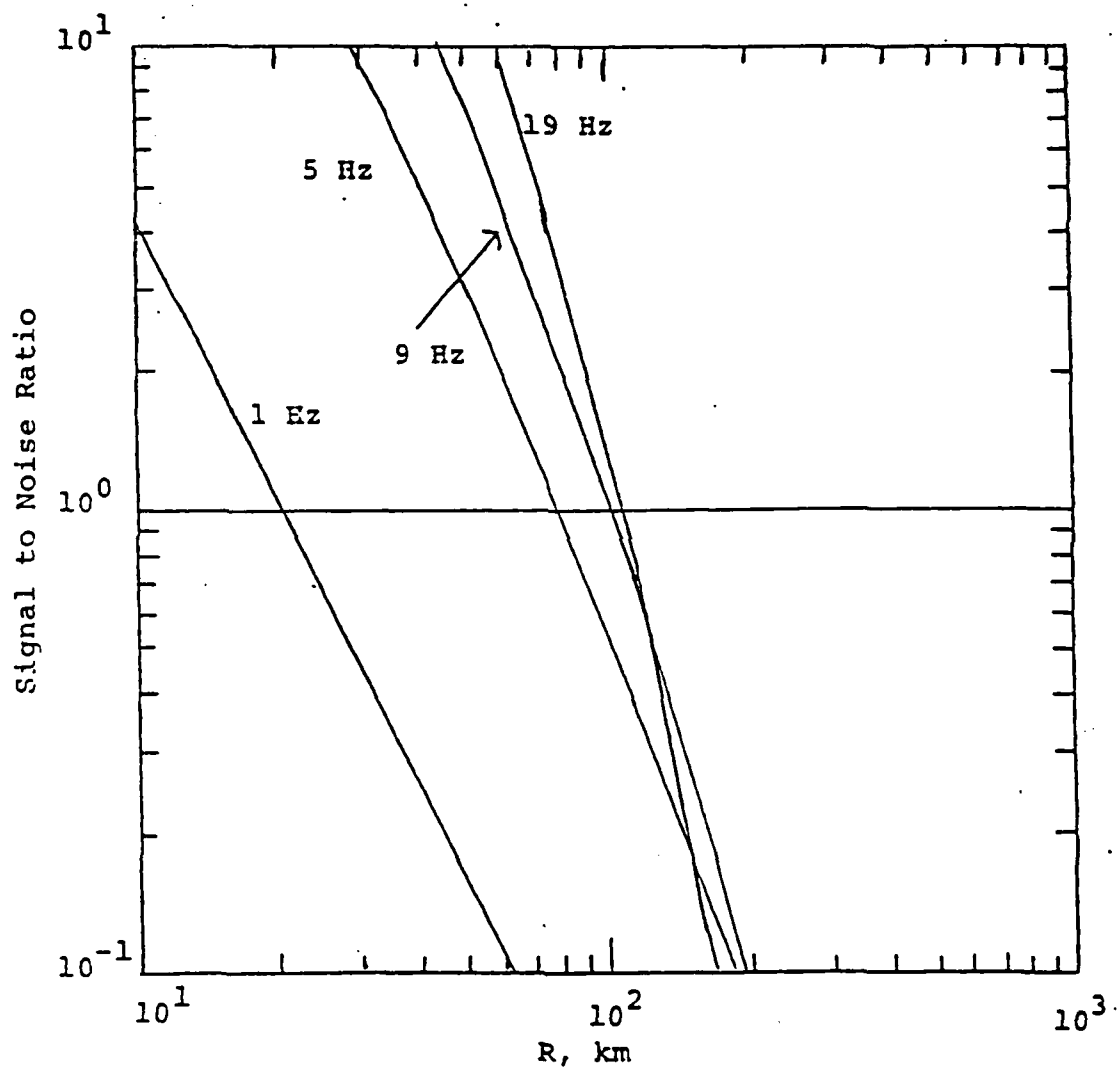


Figure 8. Predicted Detection Thresholds as a Function of Frequency for 3.7 kt in a 34 m Radius Cavity in Salt at Salmon Depth, "Minimum" Model.

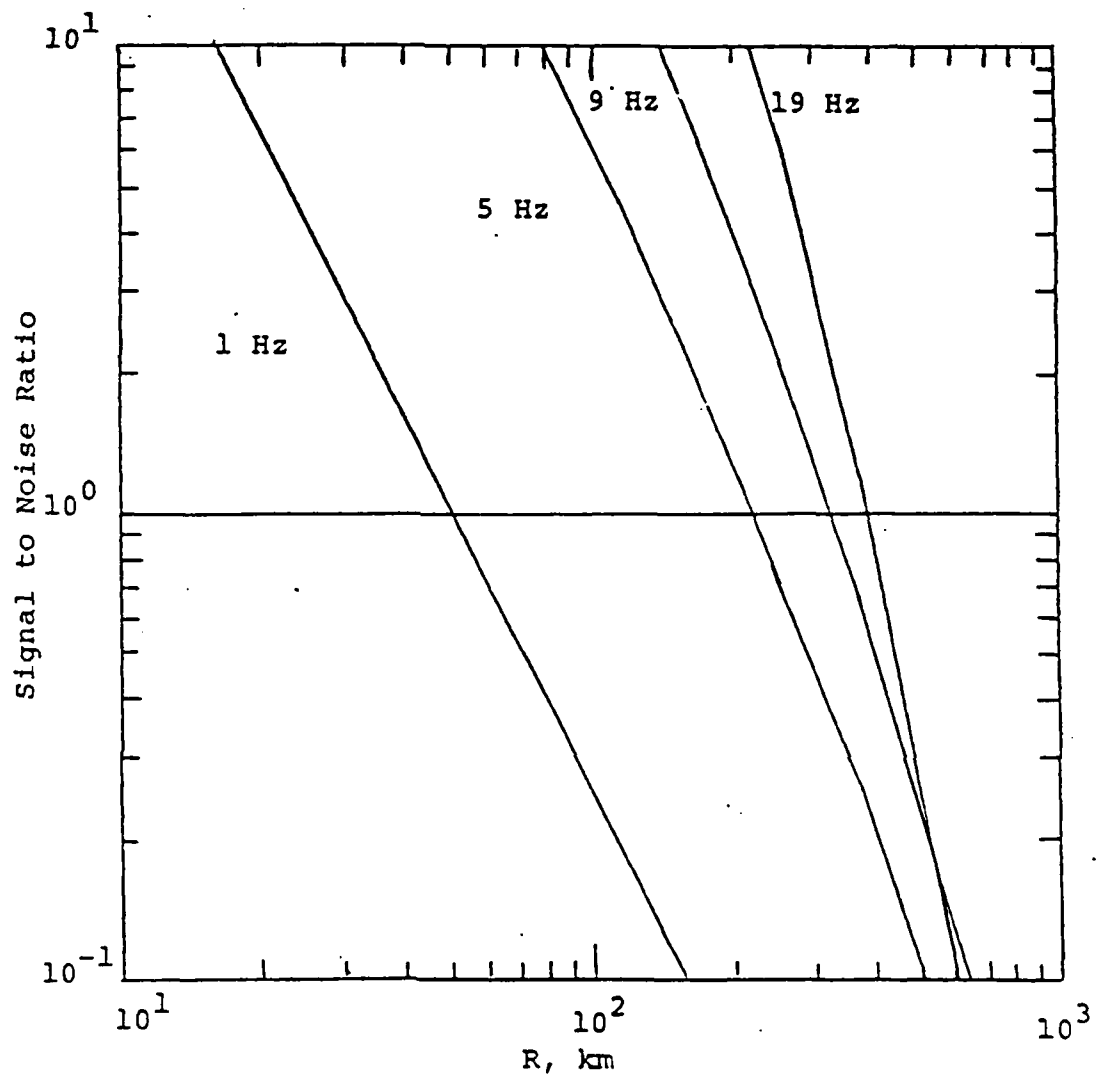


Figure 9. Predicted Detection Thresholds as a Function of Frequency for 3.7 kt in a 34 m Radius Cavity in Salt at Salmon Depth, "Maximum" Model.

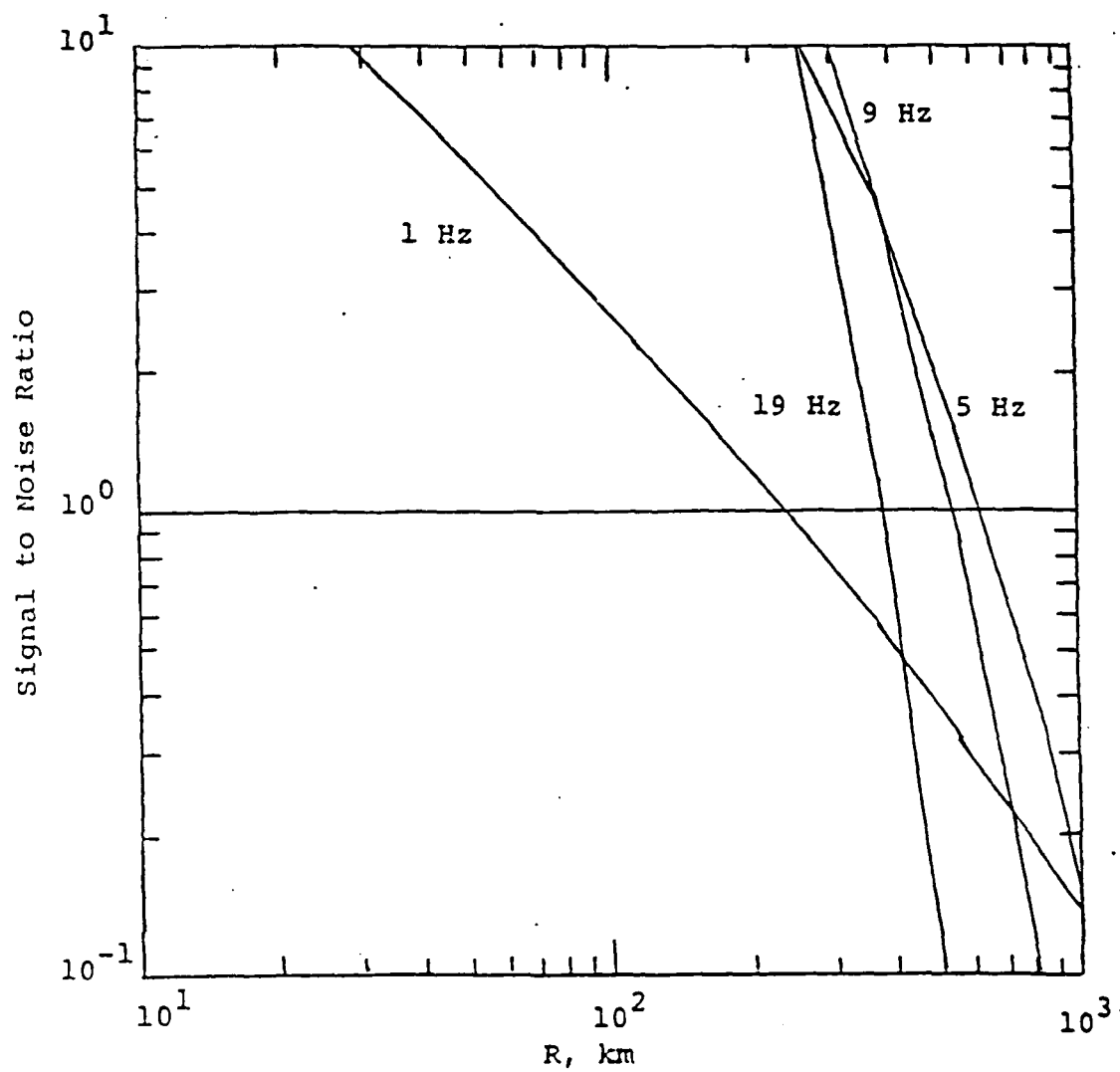


Figure 10. Predicted Detection Thresholds as a Function of Frequency for 3.7 kt in a 34 m Radius Cavity in Salt at Salmon Depth, Rodean's Model.

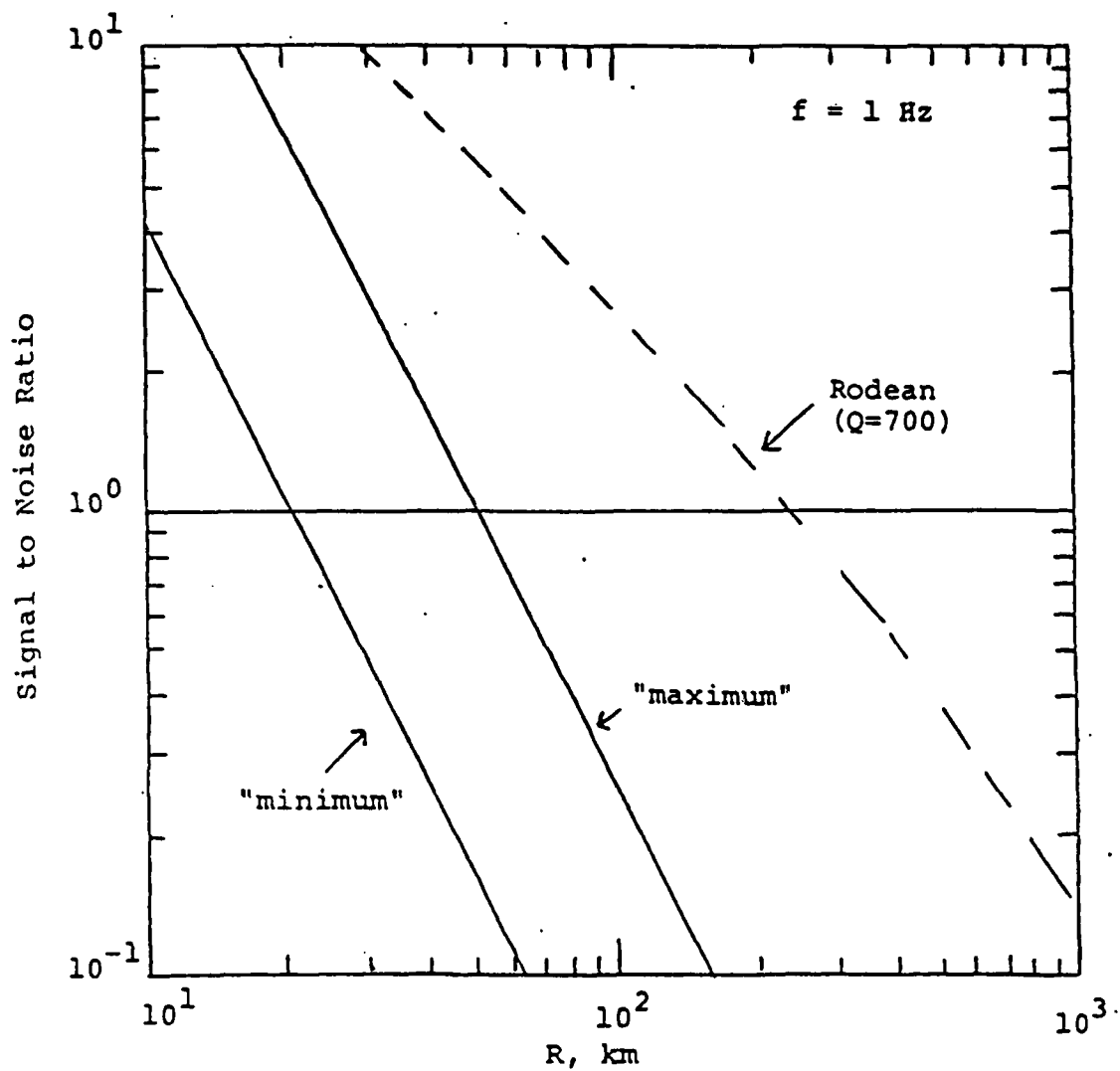


Figure 11. Comparison of Detection Thresholds Predicted by the "Minimum," "Maximum" and Rodean Models for 3.7 kt in a 34 m Radius Cavity in Salt at Salmon Depth, $f = 1.0 \text{ Hz}$.

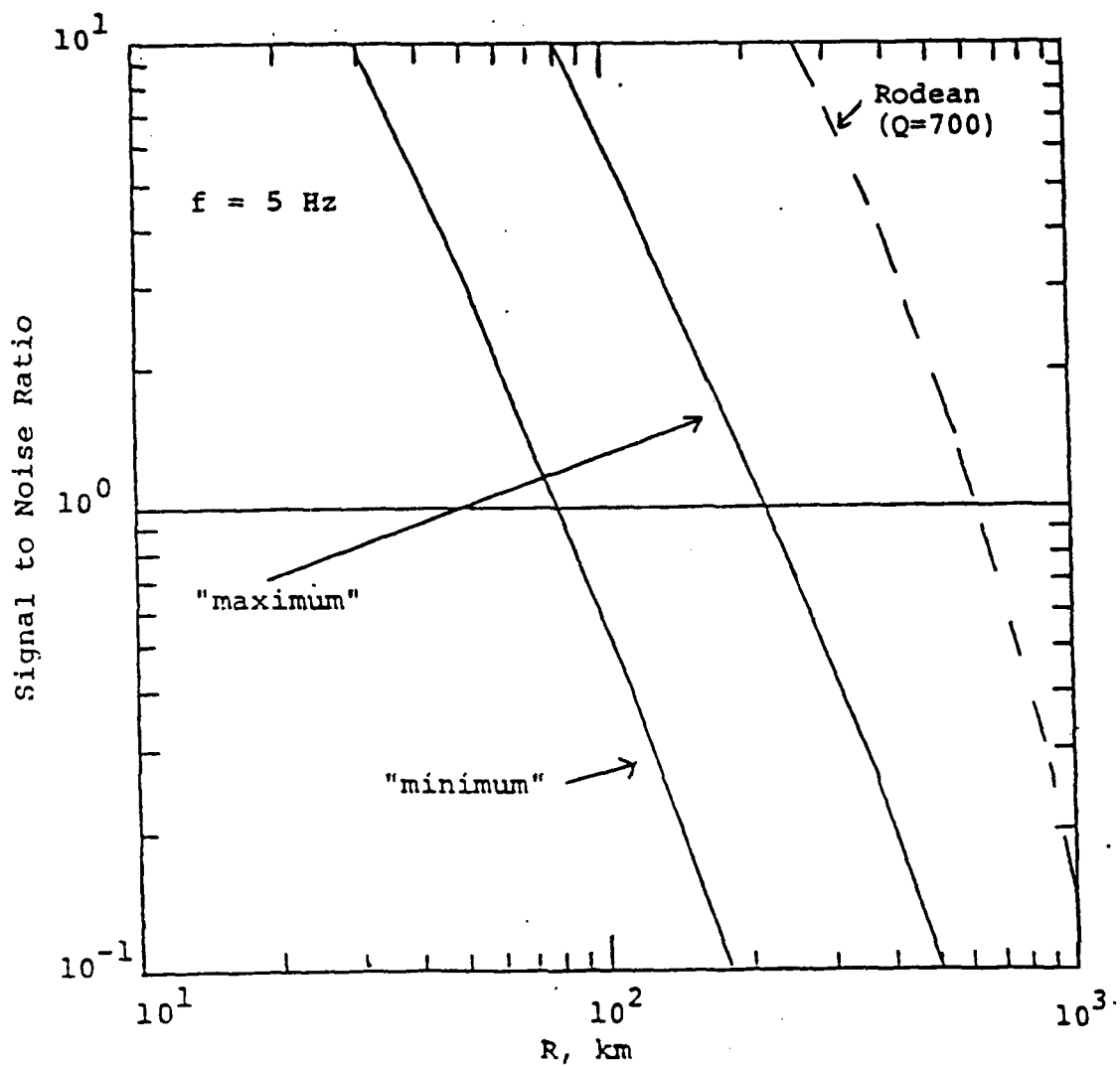


Figure 12. Comparison of Detection Thresholds Predicted by the "Minimum," "Maximum" and Rodean Models for 3.7 kt in a 34 m Radius Cavity in Salt at Salmon Depth, $f = 5.0 \text{ Hz}$.

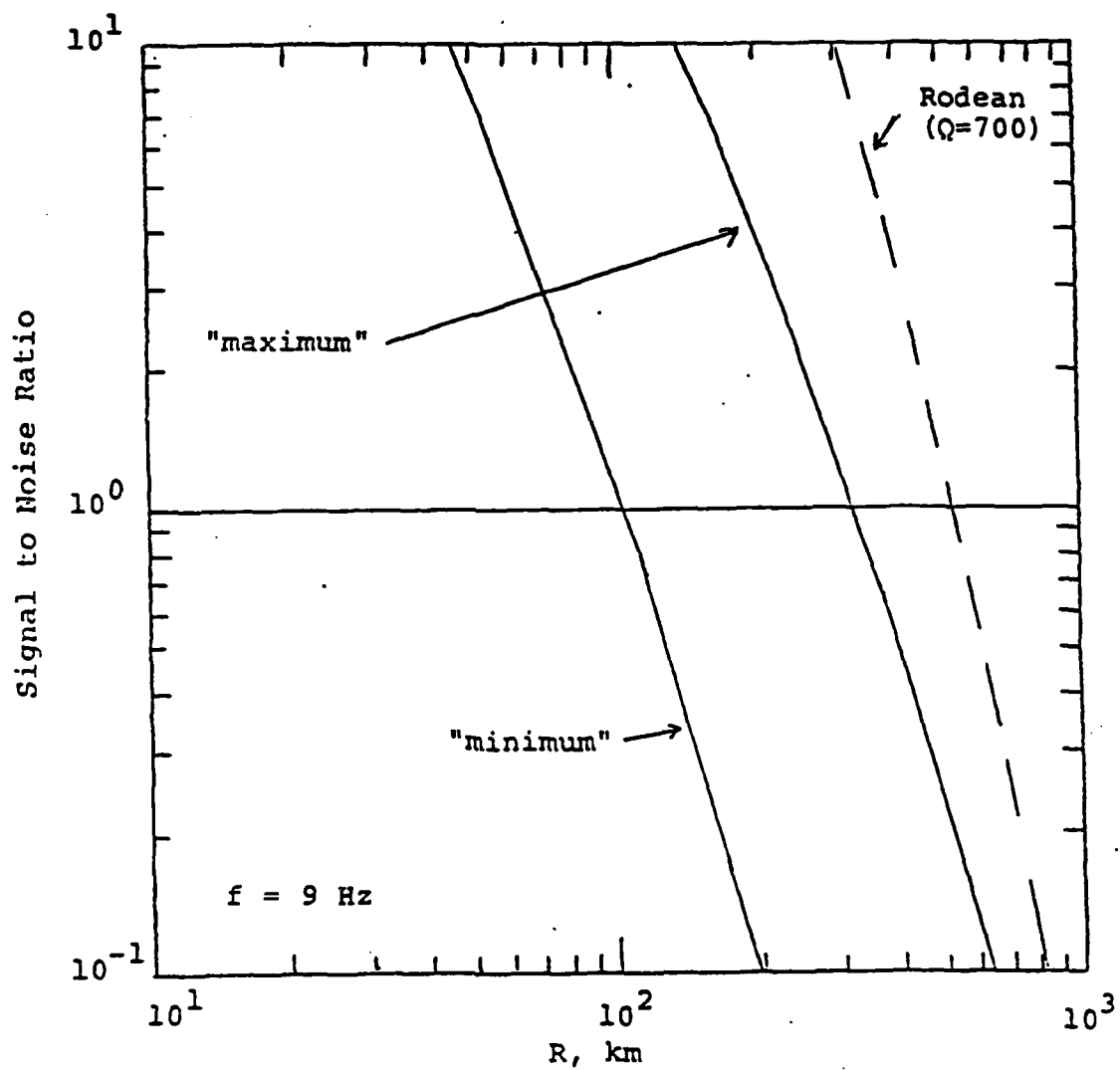


Figure 13. Comparison of Detection Thresholds Predicted by the "Minimum," "Maximum" and Rodean Models for 3.7 kt in a 34 m Radius Cavity in Salt at Salmon Depth, $f = 9.0 \text{ Hz}$.

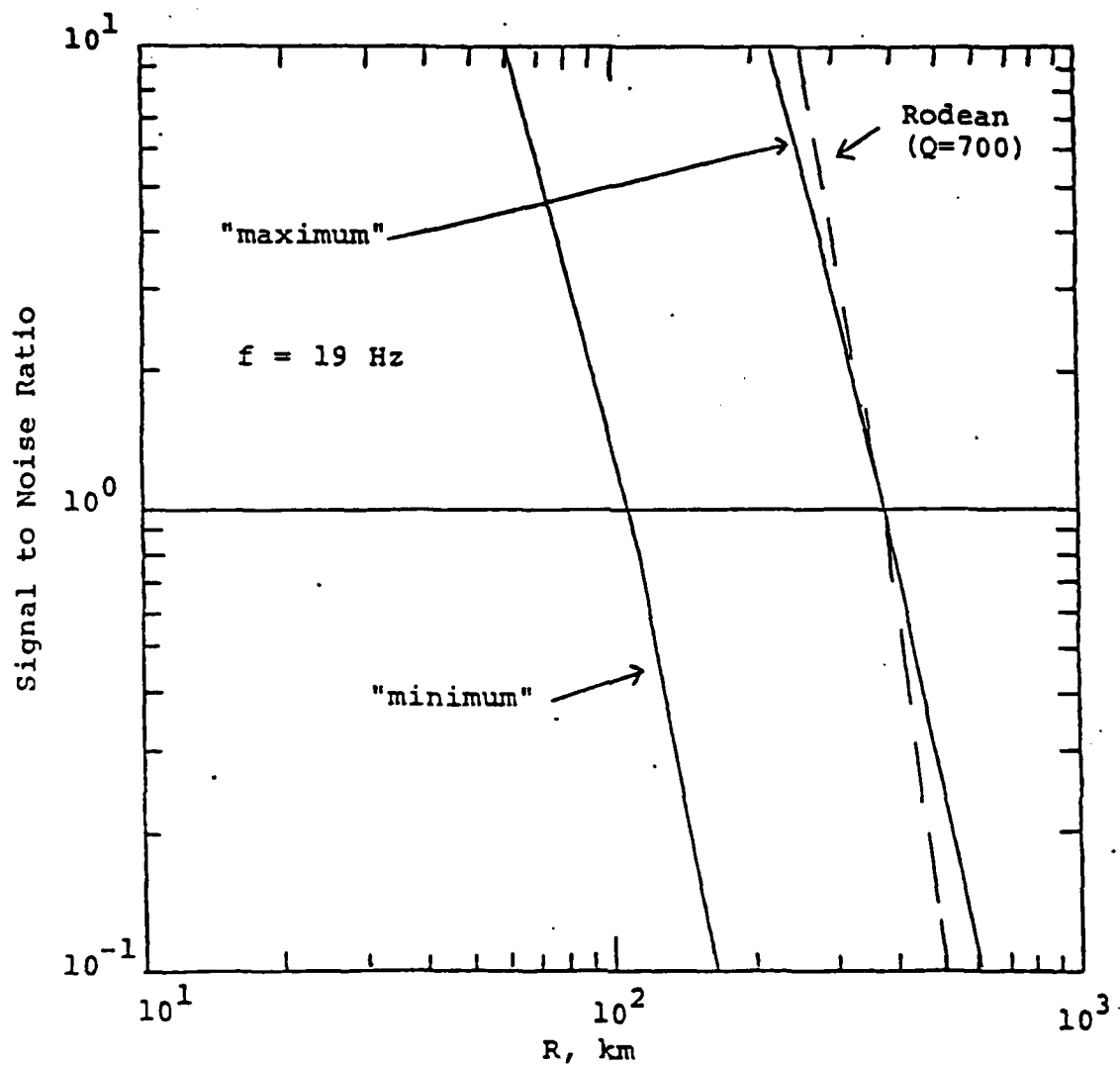


Figure 14. Comparison of Detection Thresholds Predicted by the "Minimum," "Maximum and Rodean Models for 3.7 kt in a 34 m Radius Cavity in Salt at Salmon Depth, $f = 19 \text{ Hz}$.

APPENDIX B

A FURTHER DISCUSSION OF FACTORS INFLUENCING
THE DETECTION AND DISCRIMINATION OF DECOUPLED
EXPLOSIONS AT REGIONAL DISTANCES

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ABSTRACT

From the Rodean analysis described at the February DARPA Conference on Decoupling and the Murphy discussion of that analysis, we derive, as did Rodean, the expression

$$f^* (S/N)_{\max} = \min \left\{ \begin{array}{l} \frac{2 C Q}{\pi R} \\ f_c \quad \text{source corner frequency} \end{array} \right.$$

for describing the frequency, as a function of range, at which the signal-to-noise ratio is a maximum for compressional phases from a simple model of a "Patterson Decoupled" explosion. From this expression, we suggest a logical definition of far-field range,

$$R_f > \frac{2 C Q}{\pi f_c}$$

for discussion of the detection of cavity decoupled events. We find that frequencies between $0.4f^*$ and $2f^*$ (provided f_c is not exceeded) will be within a factor of two of the optimum signal-to-noise ratio, suggesting that discrimination based on P wave amplitude-frequency relations may be feasible soon after detection levels are exceeded if high frequency data is available.

We suggest that to complete the logical "framework" for analyzing the detection of decoupled explosions, a geometric model of the deployed sensor system must be included. We point out that, if the sensors are deployed in an equilateral triangle configuration at a spacing of $2S$, then 77% of the monitored area is further than a distance of $\frac{1}{2}S$ from any sensor, 9% is further than S , and the maximum distance from any sensor is $1.15S$. Also, by deploying one additional sensor at the center of the triangle, we indicate that the area within $0.58S$ from any sensor increases from 30% to 91%. Thus the relation of R_f to S defines the relative importance of near-field and far-field attenuation effects.

INTRODUCTION.

At the February DARPA Conference on Decoupling, Rodean of LLL (Ref 1) described a preliminary model he had put together to assess the detectability of crustal P phases from decoupled explosions at regional distances. Subsequent to that description, Murphy of SSS (Ref 2) reviewed the Rodean treatment to propose reasonable optimistic and pessimistic alternatives to his assumptions. The principal result (Ref 3) of that review was the selection, by Murphy, of a refracted P wave propagation path; as opposed to the direct P wave path selected by Rodean. The purpose of this discussion is to interpret further the analyses in References 1 and 2, and to complete the logical "framework" for those analyses by suggesting the addition of a very simplified model of the deployed seismic sensor system.

Interpretation of Previous Analyses. In the interpretation of the previous analyses, we shall find it useful to highlight first the commonality in the two approaches. Both considered the following factors in their analyses:

- (i) the seismic source function
- (ii) propagation path effects
- and (iii) seismic noise model conditions at a sensor site.

As a result of both analyses, the following general expression for signal-to-noise ratio at a sensor site could thus be developed for compressional signals:

$$\begin{array}{ccc} \text{SOURCE} & \text{PATH} & \text{NOISE}^{-1} \\ SN(f) = \dot{\phi}(f) \cdot \left(\frac{A}{R^n C} \right) e^{-\frac{\pi f R}{CQ}} \cdot \frac{f^2}{B} & & (1) \end{array}$$

where $SN(f)$ is the signal-to-noise ratio for frequency f , $\phi(f)$ is the reduced velocity potential for the seismic source function, R is the source-to-sensor distance, n and A are constants depending on the

propagation mode, Q is the dissipation constant, and B is a noise amplitude constant. Thus, this general expression mathematically describes both models with the propagation path difference resulting in

$A = \frac{25}{\pi}$ and $n = 2$ in Murphy's analysis

while $A = 1$ and $n = 1$ in Rodean's analysis.

While Murphy considers, also, an alternative source function for a nuclear detonation in an underground cavity, both consider the original Latter et. al. (Ref 4) approximation of a simple step in pressure on the cavity wall. For this approximation, and by using the material properties described by Rodean, equation (1) can be simply expanded to

$$S N(f) = \begin{cases} 5 W \cdot \left(\frac{A}{R^n C} \right) e^{-\frac{\pi f R}{C Q}} \cdot \frac{f^2}{B} & \text{for } f \leq f_c \\ 5 W \left(\frac{f_c}{f} \right)^2 \cdot \left(\frac{A}{R^n C} \right) e^{-\frac{\pi f R}{C Q}} \cdot \frac{f_c^2}{B} & \text{for } f > f_c \end{cases} \quad (2)$$

where W is explosive yield in kilotons (bounded by the Patterson decoupling criterion). In equation (2), f_c is defined by the expression

$$f_c = \frac{\beta}{\pi r} \quad (3)$$

where β is the shear wave speed of the surrounding medium and r is the cavity radius. Now, as Rodean described, equation (2) can be evaluated for the frequency at which the maximum signal-to-noise ratio occurs at at any given range. First,

$$\frac{\partial S N(f)}{\partial f} = \frac{5}{B} W \frac{A}{R^n C} e^{-\frac{\pi f R}{C Q}} \left[2 f - \frac{f^2 \pi R}{C Q} \right] \quad (4)$$

for the low frequency part of equation (2). By setting equation (4) equal to zero, we find the maximum signal-to-noise occurs at

$$f = \frac{2 C Q}{\pi R} \quad (5)$$

provided that f is less than or equal f_c . From a similar analysis of the high frequency part of equation (2), we find that the maximum in equation (2) must always occur at f_c . Thus, assuming the simple source model, we find that both analytic models result in the condition that the maximum in the signal-to-noise ratio will be described by

$$f(SN^*) = f(S/N) \max = \min \left\{ \begin{array}{l} \frac{2CQ}{\pi R} \\ f_c \end{array} \right. \quad (6)$$

as illustrated in Figure 1. Further we suggest that the expression

$$R_f > \frac{2 C Q}{\pi f_c} \quad (7)$$

provides a reasonable definition for far-field behavior.

The previous discussion highlighted the frequency at which the optimum signal-to-noise ratio, for these theoretical models, occurs. This focus was as a result of signal detection concerns. However, source discrimination will also be of concern. Recent trends in discrimination studies have indicated that comparisons of a high frequency amplitude of the P-wave to a low frequency amplitude might soon become a useful discriminant that will be influenced by signal-to-noise ratios at various frequencies. Thus one can ask, at least for these models, how the signal-to-noise ratio varies about the optimum frequency, f^* . Forming the ratio $SN(f)$ to $SN^*(f^*)$ from the low frequency portion of equation (2), we find

$$SN/SN^* = \left(\frac{f}{f^*} \right)^2 e^{-2\left(\frac{f}{f^*} - 1\right)} \quad (8)$$

after some algebra. This expression (see figure 2) is in fact a direct result of the models considered and is independent of Q , C , and range.

Thus we see from figure 2 that the band of frequencies between $0.4f^*$ and $2f^*$ will be within a factor of two of the optimum signal-to-noise ratio, suggesting that discrimination may be feasible soon after detection levels are exceeded.

Complete Logical "Framework." In reviewing Rodean's and Murphy's analyses, we have felt some dicotomy in interpretation. After considering this dicotomy, and the analyses in general, we suggest that the logical "framework" suggested by Rodean, is not yet complete. In particular, we believe that a very useful addition to the model would be a simple geometric model of the deployment of the sensor system. We further believe that such a model will complete the logical framework if one assumes that all information measured by the deployed system is transmitted and used efficiently. The need for this model is defined both by the presence of near-field and far-field behaviors (as defined by equation 7), and by the yield-range-noise relationships defined by equations (1) and (2). For, in order to evaluate the importance of near-field and far-field behaviors, some relationship to monitoring area per sensor must be defined.

We suggest that the simplest, and yet most general, model of a deployed sensor system is a triangle formed by three sensors, one at each corner. This geometric arrangement is the simplest because arrangements using one, or two, sensors cannot define an area. Therefore, since the surface of the earth, or any portion thereof, is an area, models using one or two sensors cannot be related to the area to be monitored. The arrangement is the most general because any area monitored by N seismic sensors, unless all those sensors are in a common straight line, can immediately be divided into triangular subareas with the sensors at each corner. Indeed, it is not the assumption of this geometry, but the assumption of plane layered models for propagation paths, that restricts the size of the deployment model.

We shall, then, consider the equilateral triangle (figure 3) with sides of length $2S$. Now, in considering this geometric arrangement we

find that, theoretically at least, all conditions can be considered by merely considering the dashed right triangle because of symmetry. The addition of this model to the overall logical framework thus allows the importance of near-field and far-field to be assessed by aiding in the definition of percentage of area within a given distance of a single sensor as shown in figure 4. In particular, we see that approximately 77% of the area is further than $\frac{1}{2}S$ from any sensor, 9% is further than S , and one can be as far as $1.15S$ away from any sensor by being at the center (point 3 of figure 3) of the bounding triangle. Finally, we can show that the deployment of one additional sensor at the center (point 3) increases the area within a distance of $.58S$ from any sensor from 30% to 91%. Obviously, then, sensor spacing and deployment model, in addition to source, path, and noise models, are important factors influencing the detection of decoupled explosions at regional distances. However, the addition of sensor spacing and deployment models should complete the logical "framework."

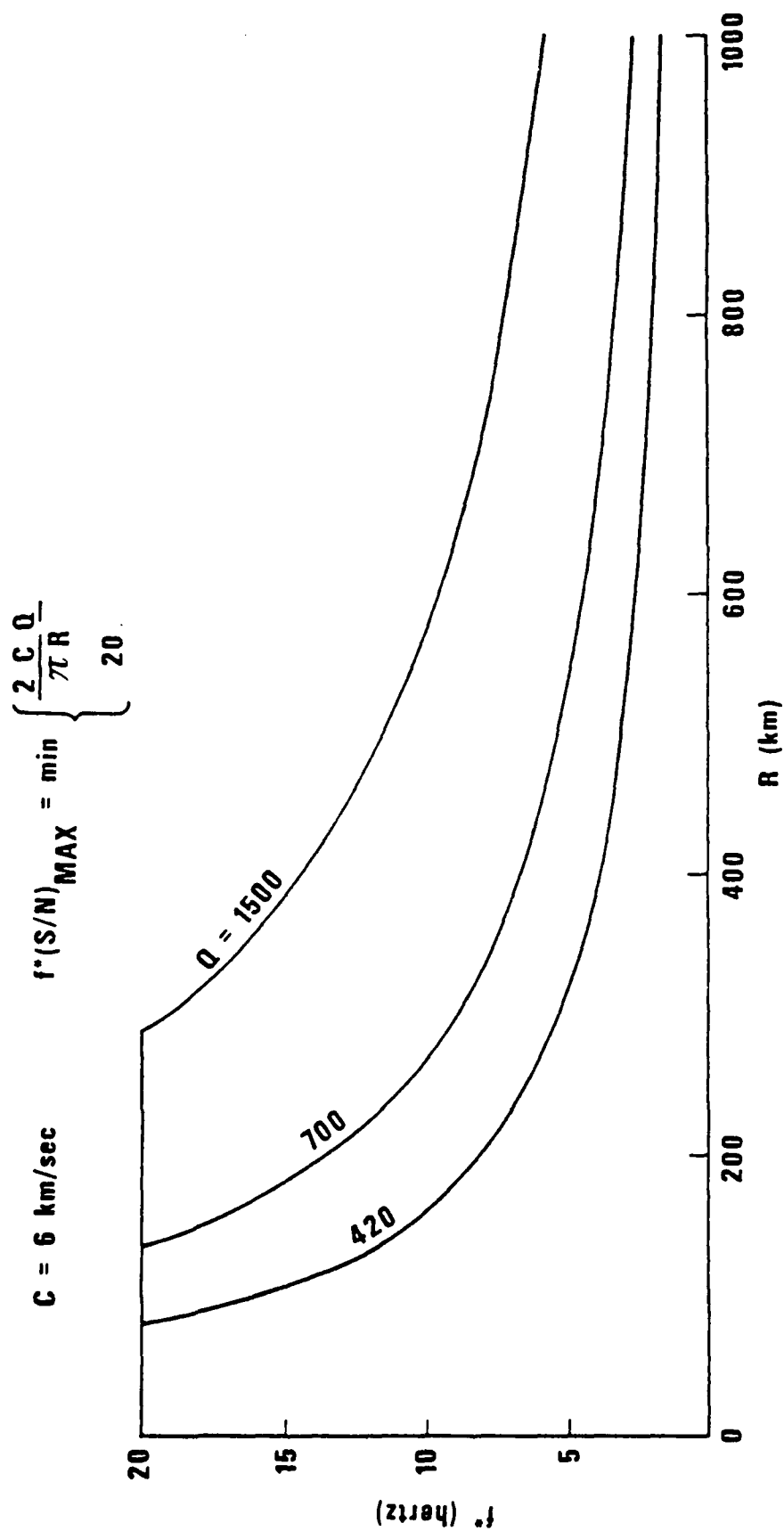


Figure 1. Optimum frequency, as a function of range (R) and attenuation constant (Q), for detection of seismic signals from a low-yield decoupled nuclear event.

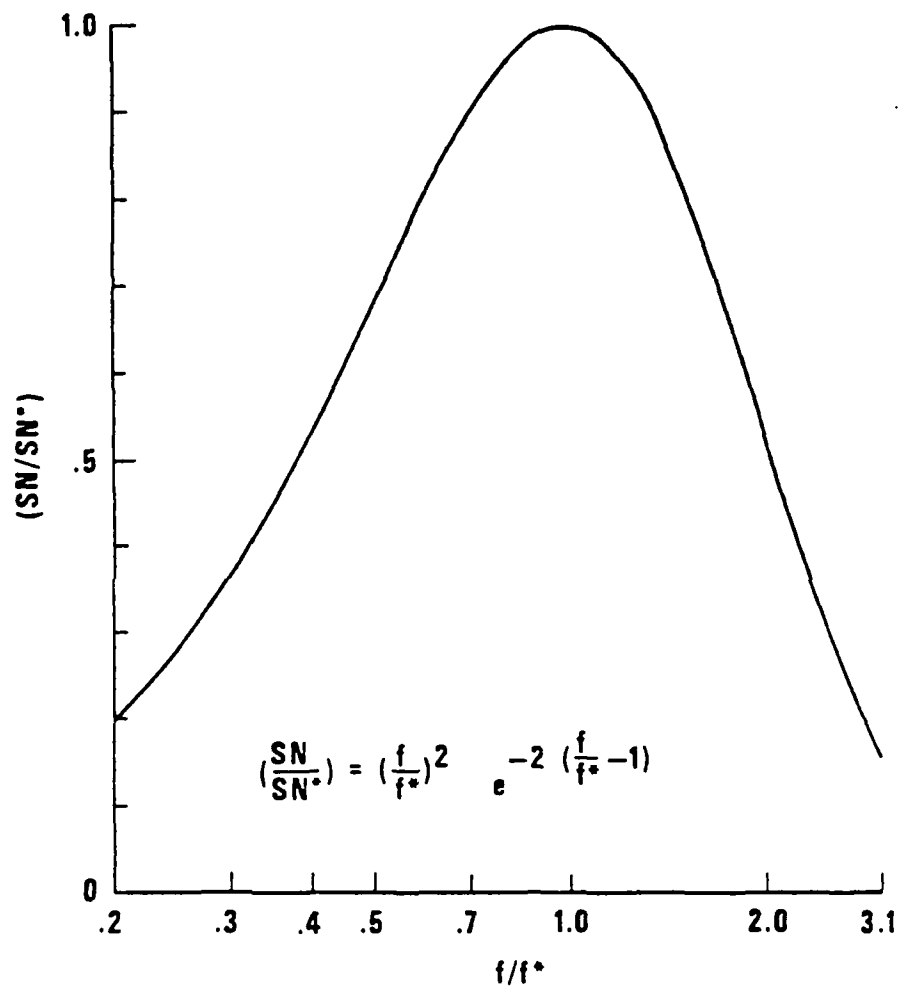


Figure 2. Relation of the signal-to-noise ratio (SN) at frequency (f) to the optimum signal-to-noise ratio (SN*) as a result of the expression shown.

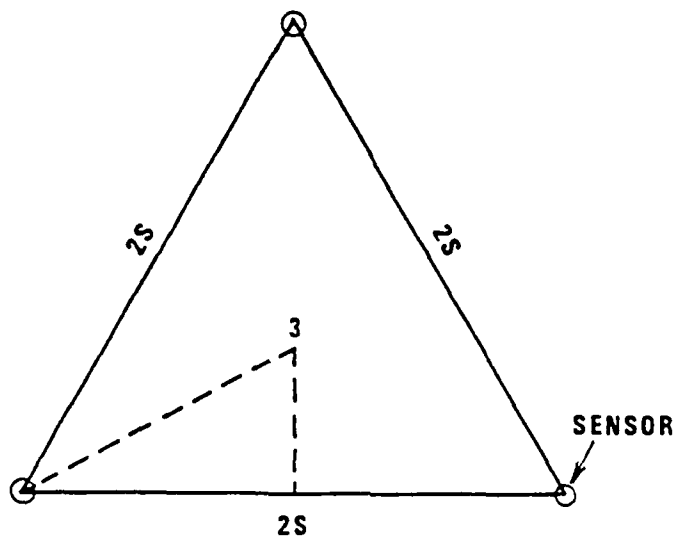


Figure 3. A basic deployment model of seismic sensors spaced at distances of $2S$. The dashed internal triangle defines the area considered in the analysis with point 3 at the center of the external triangle.

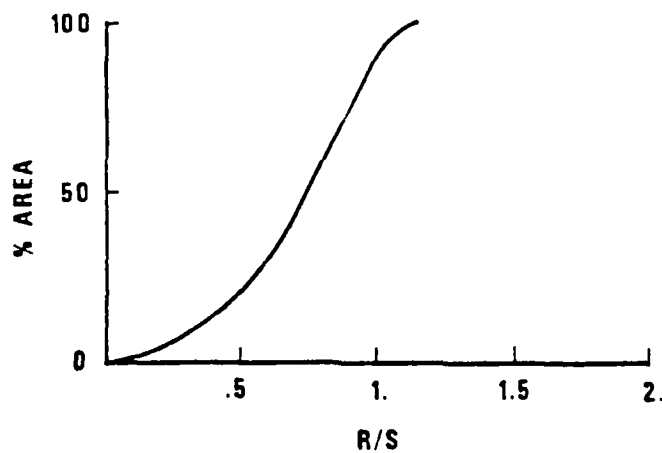


Figure 4. The percentage area within a given distance (R) from a sensor in figure 3 as a function of the ratio of R to S .

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